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FATIGUE TESTS OF WELDED JOINTS IN STRUCTURAL STEEL PLATES

A REPORT OF AN INVESTIGATION

conducted by

THE ENGINEERING EXPERIMENT STATION, UNIVERSITY OF ILLINOIS

in cooperation with

THE PUBLIC ROADS ADMINISTRATION, FEDERAL WORKS AGENCY
THE CHICAGO BRIDGE AND IRON COMPANY
THE BUREAU OF SHIPS, U. S. NAVY

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CONTENTS

PAGE

I. Introduction 7
1. Object and Scope of Investigation 7
2. Description of Fatigue Testing Machines . . . 10

II. Fatigue Tests of Butt Welds in 7/8-in. Carbon-Steel Plates 11
3. Description of Specimens and Tests 11
4. Results of Tests 12
5. Discussion of Results 24
6. Static Tests of Fatigue Specimens 33
7. Metallurgical Studies 35
8. Summary of Results 38

III. Relative Strength of Welded and Riveted Joints in Low-Alloy Steel Plates 42
9. Description of Specimens 42
10. Static Tests of Welded Joints 45
11. Static Tests of Riveted Joints 45
12. Fatigue Strength of Welded Joints 48
13. Fatigue Strength of Riveted Joints 55
14. Summary of Results 58

IV. Effect of Periods of Rest upon Fatigue Strength of Butt Welds 58
15. Description of Tests 58

V. Tests to Determine Effect of Transverse Fillet Welds upon Fatigue Strength of Steel Plates 63
16. Description of Specimens and Tests 63
17. Results of Tests 65
18. Discussion of Results 67
19. Metallurgical Studies 70
20. Summary 79

VI. Summary of Results 80
21. Summary 80

LIST OF FIGURES

NO.		PAGE
1.	Details of Specimen for Tests of Butt Welds in ⅞-in. Carbon-Steel Plates	10
2.	Details of Specimen for Rest Tests	10
3.	Location of Specimens in Parent Plates	12
4.	Details of Welding Procedure	15
5.	*S-N* Diagrams for Butt Welds in ⅞-in. Carbon-Steel Plates. Reinforcement On	18
6.	*S-N* Diagrams for Butt Welds in ⅞-in. Carbon-Steel Plates. Reinforcement Off	25
7.	*S-N* Diagrams for Butt Welds in ⅞-in. Carbon-Steel Plates Without Welds but With Mill Scale On	26
8.	Specimen Y4 With Fatigue Cracks Following Transverse Scratches Due to Grinding	28
9.	Microstructure of Weld, Specimen O1. Typical for All Specimens of ⅞-in. Carbon-Steel Plates	34
10.	Hardness Diagrams for Specimen D3. Typical for All Specimens of ⅞-in. Carbon-Steel Plates	35
11.	Fatigue Crack Through Weld in ⅞-in. Carbon-Steel Plate With Reinforcement Machined Off	36
12.	Nuclei of Butt Welds in ⅞-in. Carbon-Steel Plates That Failed in the Weld. Reinforcement Ground Off	37
13.	Fracture of ⅞-in. Carbon-Steel Plate Without Weld Showing Single Nucleus Near Center. Specimen PP3	38
14.	Fatigue Strength of Butt Welds in ⅞-in. Carbon-Steel Plates for Various Types of Specimens and for Various Relations of Minimum to Maximum Stress. Summary of Results	40
15.	Details of Riveted Specimens	41
16.	Details of Welded Specimens	42
17.	Butt Welds in Alloy-Steel Plates After Static Failure. Specimens 105 and 107	44
18.	Sketch of Riveted Specimen Showing Location of Slip Holes	45
19.	Load–Slip Relation for Specimens 91, 92, and 93	46
20.	Riveted Joints After Static Failure. Specimens 91 and 92	47
21.	Riveted Joints After Static Failure. Specimen 93	48
22.	*S-N* Diagrams for Riveted and Welded Joints in Low-Alloy-Steel Plates. Stress Cycle: Tension to Equal Compression	49
23.	Specimen 104 After Fatigue Failure	50
24.	Fisheyes Developed in Fatigue Tests of Low-Alloy Specimens That Broke in the Weld	52
25.	Microstructure of Weld in Low-Alloy-Steel Plate. Specimen 103	54
26.	Hardness Diagrams for Butt Weld in Low-Alloy-Steel Plate. Specimen 103	55
27.	Fatigue Crack That Originated at Edge of Plate Where the Fillet Joined the Tangent. Specimen 96	56
28.	Typical Fatigue Failure of Plate of Riveted Joint. Low-Alloy-Steel Plate	56
29.	*S-N* Diagrams for Butt Welds in ½-in. Carbon-Steel Plates	61
30.	Details of Specimens	63
31.	Stress–Strain Diagrams for Carbon-Steel Plates and Low-Alloy-Steel Plates	65
32.	*S-N* Diagrams for Carbon-Steel Plates and Low-Alloy-Steel Plates	69

NO. PAGE
33. Butt and Fillet Weld Gage 70
34. Typical Fillet Welds for Carbon-Steel Plates 71
35. Typical Fillets of Alloy-Steel Plates 71
36. Hardness Diagrams for Specimen 14. Typical for All Carbon-Steel Specimens 74
37. Microstructure of Specimen 8. Typical for All Carbon-Steel Specimens 75
38. Hardness Diagrams for Specimen 43. Typical for All Alloy-Steel Specimens 76
39. Microstructure of Specimen 49. Typical for All Alloy-Steel Specimens . . 77
40. Fatigue Crack Through Heat-Affected Zone 78

LIST OF TABLES

NO. PAGE
1. Schedule of Tests of Butt Welds in ⅞-in. Carbon-Steel Plates 13
2. Physical Properties of ⅞-in. Carbon-Steel Plates 14
3. Chemical Composition of ⅞-in. Carbon-Steel Plates 15
4. Details of Welding Procedure: Butt Welds in ⅞-in. Carbon-Steel Plates . 16
5. Classification of Welds From Radiographs: ⅞-in. Carbon-Steel Plates . . 16
6. Strength of Butt Welds in ⅞-in. Carbon-Steel Plates in the As-Welded Condition 17
7. Strength of Butt Welds in ⅞-in. Carbon-Steel Plates. Reinforcement On. Stress-Relieved 19
8. Strength of Butt Welds in ⅞-in. Carbon-Steel Plates. Reinforcement Machined Off. Not Stress-Relieved 20
9. Strength of Butt Welds in ⅞-in. Carbon-Steel Plates. Reinforcement Machined Off. Stress-Relieved 21
10. Strength of Butt Welds in ⅞-in. Carbon-Steel Plates. Reinforcement Ground Off. Not Stress-Relieved 22
11. Strength of Butt Welds in ⅞-in. Carbon-Steel Plates Without Welds but With Mill Scale On 23
12. Strength of Butt Welds in ⅞-in. Carbon-Steel Plates. Reinforcement and Mill Scale Planed Off 24
13. Relation Between Radiograph Rating and Fatigue-Strength Rating for Specimens With Reinforcement On 26
14. Relation Between Radiograph Rating and Fatigue-Strength Rating for Specimens With Reinforcement Machined Off 27
15. Relation Between Reinforcement Rating and Fatigue-Strength Rating of Butt Welds in ⅞-in. Carbon-Steel Plates 30
16. Effect of Eccentricity of Load Upon Fatigue Strength of Specimen: ¾-in. Carbon-Steel Plate Without Weld but With Mill Scale On Both Sides 31
17. Static Strength of Fatigue Specimens 32
18. Fatigue Strength of Butt Welds in ⅞-in. Carbon-Steel Plates. Summary of Results 39
19. Chemical Composition of Cores of Electrodes, Plates, and Deposited Weld Metal 43
20. Results of Static Tests of Welded Joints 43
21. Results of Static Tests of Riveted Joints 47
22. Results of Fatigue Tests of Welded Joints: Low-Alloy-Steel Plates . . 49
23. Results of Fatigue Tests of Riveted Joints: Slip Between Plates 57

NO. PAGE
24. Results of Fatigue Tests of Riveted Joints: Low-Alloy-Steel Plates . . . 57
25. Physical Properties of Plates and Chemical Composition of Plates and Weld Metal Used in Rest Tests 59
26. Effect of Periods of Rest Upon Fatigue Strength of Butt Welds in ½-in. Carbon-Steel Plates 60
27. Effect of Periods of Rest Upon Fatigue Strength of Butt Welds in ½-in. Carbon-Steel Plates; Summary of Results 62
28. Physical Properties of Base Plates 64
29. Chemical Composition of Plates and Weld Metal 66
30. Data Relating to Welding 66
31. Fatigue Strength of Plates With Transverse Fillet Welds; Carbon-Steel Plates 67
32. Fatigue Strength of Plates With Transverse Fillet Welds; Alloy-Steel Plates 68
33. Fatigue Strength of Plates With Transverse Fillet Welds; Summary . . 70
34. Rating of Beads from Profile 72
35. Fatigue-Strength Rating 72
36. Relation Between Bead Rating and Fatigue–Strength Rating 73

FATIGUE TESTS OF WELDED JOINTS IN STRUCTURAL STEEL PLATES

I. Introduction

1. *Object and Scope of Investigation.*—The primary object of this investigation was to obtain information on which to base specifications governing the design of welded structural members subjected to either reversed or pulsating stresses.

One of the deterrents to the use of welds as a means of fabricating bridges has been a lack of knowledge of the fatigue strength of welded joints. Engineers who had become accustomed to thinking of the static strength of carbon structural steel as being of the order of 63 000 lb. per sq. in., and of the fatigue strength of machined specimens of the same material as being of the order of 47 000 lb. per sq. in.,* were somewhat disturbed by the reports of early European tests which showed a fatigue strength of structural members connected by welds as low in some instances as 15 000 lb. per sq. in. The situation indicated clearly that fatigue tests of welded joints, as large as it was feasible to test, would have to be made before American engineers would fabricate bridges by welding. Realizing this situation, the Welding Research Committee of the Engineering Foundation organized a committee, known as Committee F, to plan and carry out an investigation such as appeared to be needed. This bulletin is a progress report of the resulting investigation. The tests have been planned by Committee F, of which Jonathan Jones† is chairman, and they have been financed by the Chicago Bridge and Iron Company, the Public Roads Administration, Federal Works Agency, and the Bureau of Ships of the United States Navy. The Carnegie-Illinois Steel Corporation, the Bethlehem Steel Company, Lukenweld, Inc., the Bureau of Ships, the G. E. X-Ray Corporation, the Chicago Bridge and Iron Company, the Lincoln Electric Company, and the Lasker Boiler and Engineering Corporation contributed materials and services. The tests were made at the University of Illinois.

The members of Committee F were:

Jonathan Jones, Chairman, Chief Engineer, Fabricated Steel Construction, Bethlehem Steel Company, Bethlehem, Pa.

*This is for a cycle in which the stress varies from 0 to tension and for failure at 2 000 000 cycles. For complete reversal and for failure at a much greater number of cycles the fatigue strength would, of course, be still less.

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The fatigue strength of a member, as the term is used in this bulletin, is the maximum stress in a stress cycle that caused failure at a definite stated number of cycles when the ratio of the minimum to the maximum stress in the cycle had a definite stated value. Three ranges of minimum to maximum stress were used in this investigation:

(1) from a given tensile stress to an equal compressive stress;

(2) from zero stress to some given tensile stress;

(3) from a given tensile stress to a tensile stress one-half as great.

The ratio of the minimum to the maximum stress has been designated by r. The values of r for the cycles listed are -1.0, 0.0, and $+0.5$. In general, seven identical specimens were tested for each value of r. For three, the maximum stress in the stress cycle was so chosen as to cause failure, as nearly as it was possible to estimate in advance, at 100 000 cycles; for three, the maximum stress was chosen for failure at 2 000 000 cycles; and the remaining specimen was used as a spare to be tested as seemed desirable after the other six tests had been completed. It is not possible to select a stress to cause failure at exactly a predetermined number of cycles. The practice was followed of reporting the actual stress in the stress cycle and the actual number of cycles for failure, and also reporting the fatigue strength corresponding to failure at either 100 000 cycles or at 2 000 000 cycles, computed from the actual stress and number of cycles by the use of the empirical equation $F = S\,(n/N)^K$, in which F is the fatigue strength corresponding to failure at N cycles, S is the maximum unit stress in the stress cycle which caused failure at n cycles, and K is an experimental constant whose value depends upon the stress-raising characteristics of the specimen. Although it is an empirical equation it is fairly accurate if the ratio n/N does not vary too much from unity.

The stress over a transverse section of a member subjected to a centric longitudinal force is not uniform. Instead, every surface indentation, scratch, or change in section, and every internal void or inclusion, acts as a stress raiser and causes an intensity of stress in its immediate vicinity that greatly exceeds the average stress over the section. Although this is realized, the term stress has been used to

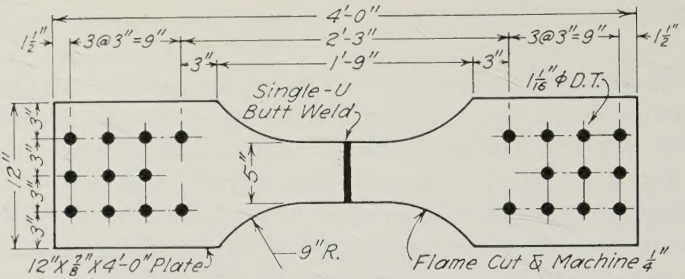


FIG. 1. DETAILS OF SPECIMEN FOR TESTS OF BUTT WELDS IN ⅞-IN. CARBON-STEEL PLATES

designate the quotient obtained by dividing the total longitudinal force by the area of the transverse section, since the stress was nominally axial for all tests.

The tests described in this bulletin were planned to determine the following:

(1) The fatigue strength of butt welds in ⅞-in. carbon-steel plates of structural grade

(2) The relative fatigue strength of welded and riveted joints in low-alloy plates of structural grade

(3) The effect of frequent periods of rest upon the fatigue strength of butt welds in carbon-steel plates of structural grade

(4) The effect of transverse fillet welds upon the fatigue strength of plates.

The fatigue tests were supplemented with static tests and metallurgical studies.

2. *Description of Fatigue Testing Machines.*—There were two machines of each of two types. The large machines, which have a rated capacity of 200 000 lb., had been used in the fatigue tests of

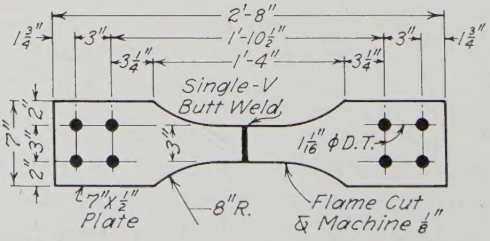


FIG. 2. DETAILS OF SPECIMEN FOR REST TESTS

riveted joints and are described in detail in the report of those tests.* The smaller machines had a capacity of 50 000 lb. and were designed and specially built for these tests. All machines were of the mechanical type and produced an axial stress in the specimen. They could be adjusted so as to give any desired ratio of minimum to maximum stress from a complete reversal to a fluctuating stress in either tension or compression. A typical specimen for the 200 000-lb. machine is shown in Fig. 1 and one for the 50 000-lb. machine is shown in Fig. 2. The machines ran at a speed of approximately 180 r.p.m. and operated day and night without an attendant.

II. Fatigue Tests of Butt Welds in $\frac{7}{8}$-in. Carbon-Steel Plates

3. *Description of Specimens and Tests.*—The details of the specimens used in the tests to determine the fatigue strength of butt welds in carbon-steel plates of structural grade are shown in Fig. 1. All specimens were cut from two parent plates, each 126 in. x $\frac{7}{8}$ in. x 24 ft., both of which were rolled from the same ingot. The location of the individual specimens in the parent plates is shown in Fig. 3, the specimen numbers on this drawing corresponding to the specimen numbers in Table 1. Standard tension control specimens, numbers X1 to X12, were cut from the plates at points indicated in the figure. Samples for chemical analyses were taken at points indicated by small circles and numbered 1 to 16. The physical properties of the material determined from the tests of the control specimens are given in Table 2, and the chemical composition is given in Table 3. The details of the welding procedure are given in Table 4 and Fig. 4.

In order to study the factors that influence the fatigue strength of welds, some specimens were tested in the as-welded condition, for some the reinforcement was *planed* flush with the surface of the base plate on both sides, and for others it was *ground* flush with the base plate on both sides with a portable grinder. Some specimens with the reinforcement on and some with the reinforcement off were stress-relieved by heating to a temperature of 1200 deg. F. for one hour and then cooling in the furnace. The others were not stress-relieved. Specimens without welds, but having the same outline and cut from the same parent plates as the welded specimens, were used in control tests to determine the relative fatigue strength of welds and of plates without welds but with mill scale on the two sides. A few specimens,

*Univ. of Ill. Eng. Exp. Sta. Bul. 302.

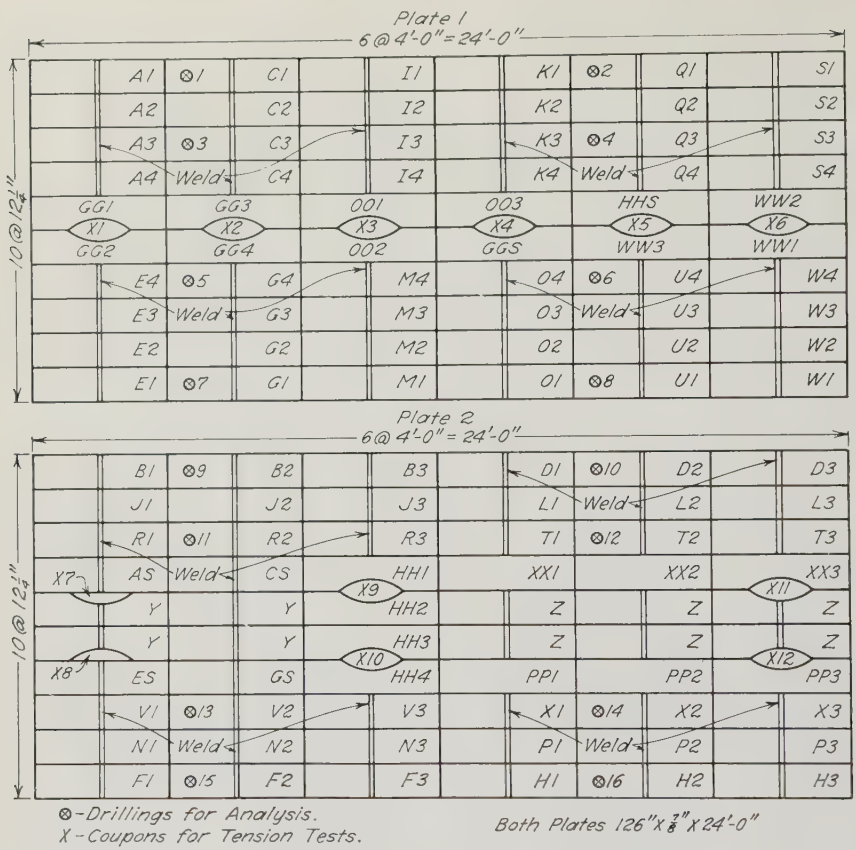


Plate 1
6@4'-0"=24'-0"
10@12"=10'-0"
A1 ⊗1 C1 I1 K1 ⊗2 Q1 S1
A2 C2 I2 K2 Q2 S2
A3 ⊗3 C3 I3 K3 ⊗4 Q3 S3
A4 Weld C4 I4 K4 Weld Q4 S4
GG1 GG3 001 003 HHS WW2
X1 X2 X3 X4 X5 X6
GG2 GG4 002 GG5 WW3 WW1
E4 ⊗5 G4 M4 04 ⊗6 U4 W4
E3 Weld G3 M3 03 Weld U3 W3
E2 G2 M2 02 U2 W2
E1 ⊗7 G1 M1 01 ⊗8 U1 W1
Plate 2
6@4'-0"=24'-0"
10@12"=10'-0"
B1 ⊗9 B2 B3 D1 ⊗10 D2 D3
J1 J2 J3 L1 Weld L2 L3
R1 ⊗11 R2 R3 T1 ⊗12 T2 T3
X7 A5 Weld C5 HH1 XX1 XX2 XX3
X9 X11
Y HH2 Z Z Z
Y HH3 Z Z Z
X10 X12
X8 E5 G5 HH4 PP1 PP2 PP3
V1 ⊗13 V2 V3 X1 ⊗14 X2 X3
N1 Weld N2 N3 P1 Weld P2 P3
F1 ⊗15 F2 F3 H1 ⊗16 H2 H3
⊗-Drillings for Analysis.
X-Coupons for Tension Tests.
Both Plates 126"x 7/8"x 24'-0"

Fig. 3. Location of Specimens in Parent Plates

some with and some without welds, were tested after the mill scale had been machined off and the surfaces polished.

Radiographs were made of all welds tested, and the specimens were rated according to the flaws revealed. The ratings, based on the classification described at the bottom of the table, are given in Table 5. It is of interest to note that of the 94 specimens tested, 54 per cent were given an A rating, 42 per cent were given a B rating, only 3 per cent were given a C rating, and only 1 per cent were given a D rating. That is, only 4 per cent had more than a very small amount of porosity.

4. *Results of Tests.*—The results of the tests of the butt welds in ⅞-in. carbon-steel plates in the as-welded condition are given in

TABLE 1
SCHEDULE OF TESTS OF BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES

	Reinforcement	Stress Relieved	Number of Cycles in 1000's	Cycle*	Specimen Numbers: Fatigue Tests	Specimen Numbers: Static Tests
Plate Without Weld	None	No	100	A B C	GG1, GG2, GG3 001, 002, 003 WW1	GGS
			2000	A B C	HH1, HH2, HH3, HH4, GG4 PP1, PP2, PP3, HHS XX1, XX2, XX3	HHS
Butt Welds	On	Yes	100	A B C	A1, A2, A4 I1, I2, I3, I4 Q1, Q2, Q3	AS
			2000	A B C	B1, B2, B3, A3 J1, J2, J3 R1, R2, R3, Q4	
		No	100	A B C	C1, C2, C3 K1, K2, K3, K4 S1, S2, S3	CS
			2000	A B C	D1, D2, D3, C4 L1, L2, L3 T1, T2, T3, S4	
	Machined Off	Yes	100	A B	E1, E2, E3 M1, M2, M3	ES
			2000	A B C	F1, F2, F3, E4, M4, V2 N1, N2, N3 V1, U1, U2	
		No	100	A B C	G1, G2, G3, G4 01, 02, 03 W1, W2, W3	GS
			2000	A B	H1, H2, H3 P1, P2, P3, 04	
	Ground Off	No	100	A	Y1, Y2, Y3	
			2000	B	Z1-1, Z1-2, Z1-3, Z2-1, Z2-2, Z2-3, Y4	
	Machined Off†	Yes	100	B	U3, U4	
		No	100	B	X2, X3	
Plate Without Weld	None†	No	100	B	WW2, WW3	

*Cycles were:
A – Tension to an equal compression.
B – 0 to tension.
C – Tension to tension ½ as great.
†Mill scale machined off and surface polished.

Table 6. The specimen number is given in column 1 and the number of the parent plate from which the specimen was cut is given in column 2. Thus specimens C1, C2, C3, and C4 were cut from plate 1, shown in Fig. 3, whereas D1, D2, and D3 were cut from plate 2. The limiting stress in the stress cycle, S, and the number of cycles for failure, n, are given in columns 3 and 4, respectively. The two values

TABLE 2
PHYSICAL PROPERTIES OF $\frac{7}{8}$-IN. CARBON-STEEL PLATES

Specimen No.	Strength, lb. per sq. in.		Elongation in 8 in. per cent	Reduction of Area per cent
	Yield Point	Ultimate		
		Plate 1		
X1	37 000	65 800	28.8	47.6
X2	34 700	63 800	30.5	50.5
X3	35 700	62 300	31.4	53.5
X4	36 600	63 100	28.2	52.2
X5	36 600	63 100	32.2	53.7
X6	36 500	63 200	30.6	53.1
Av.	36 200	63 500	30.3	51.8
		Plate 2		
X7	31 400	58 200	30.0	57.0
X8	34 200	62 200	32.3	54.5
X9	35 300	58 800	31.6	56.5
X10	34 800	60 000	33.8	55.5
X11	32 200	58 200	30.6	56.0
X12	32 300	57 200	33.6	56.5
Av.	33 400	59 100	32.0	56.0

of the fatigue strength F, one corresponding to failure at 100 000 cycles and the other to failure at 2 000 000 cycles, are given in columns 6 and 7. These values were computed from the data in columns 3 and 4 by the use of equation $F = S\,(n/N)^K$, as explained in Section 1. This equation, being empirical, is not really applicable if the ratio n/N varies too greatly from unity; nevertheless, values of the fatigue strength corresponding to failure at both 100 000 cycles and 2 000 000 cycles have been computed for all tests. The fatigue strengths based upon values of n/N varying too greatly from unity are marked with a small solid circle, which indicates that the values may not be accurate, and such values were not combined with those not so marked in computing the averages. The values marked with the circle are, however, of some interest, as a comparison of the average of values so marked and the average of corresponding values not marked affords a means of judging the accuracy of the empirical equation when used to extrapolate beyond the limits for which it was intended, thereby also indicating its accuracy when used within reasonable limits.

Most of the specimens that were tested for failure at a comparatively small number of cycles were cut from plate 1 and those that were tested for failure at a comparatively large number of cycles were

TABLE 3
CHEMICAL COMPOSITION OF ⅞-IN. CARBON-STEEL PLATES

Specimen No.	Carbon	Manganese	Silicon	Copper	Phosphorus	Sulphur
			Plate 1			
1	0.28	0.48	0.01	0.03	0.016	0.034
2	0.30	0.48	0.01	0.03	0.014	0.029
3	0.31	0.49	0.03	0.03	0.015	0.036
4	0.25	0.48	0.02	0.02	0.013	0.032
5	0.31	0.48	0.01	0.03	0.015	0.040
6	0.25	0.48	0.01	0.03	0.014	0.032
7	0.28	0.49	0.01	0.03	0.014	0.033
8	0.27	0.49	0.01	0.02	0.015	0.035
Av.	0.28	0.48	0.01	0.03	0.015	0.034
			Plate 2			
9	0.24	0.48	0.03	0.02	0.015	0.034
10	0.23	0.47	0.01	0.03	0.014	0.028
11	0.23	0.48	0.03	0.03	0.014	0.032
12	0.23	0.46	0.02	0.02	0.013	0.035
13	0.23	0.47	0.01	0.02	0.012	0.032
14	0.20	0.48	0.01	0.02	0.014	0.031
15	0.24	0.47	0.01	0.03	0.016	0.035
16	0.22	0.47	0.01	0.02	0.014	0.035
Av.	0.23	0.47	0.02	0.02	0.014	0.033
			Filler Metal Machined from Specimens			
A2	0.10	0.54	0.18	0.02	0.017	0.028
B3	0.08	0.51	0.18	0.02	0.018	0.031
D1	0.09	0.48	0.16	0.03	0.017	0.035
C1	0.08	0.52	0.17	0.03	0.014	0.031
Av.	0.09	0.51	0.17	0.03	0.017	0.031

cut from plate 2. The average strength of the control specimens was 63 500 lb. per sq. in. for plate 1 and 59 100 lb. per sq. in. for plate 2. That is, the plates for specimens tested for failure at a small number of cycles were 7 per cent stronger, statically, than the plates for specimens tested for failure at a large number of cycles. Fatigue tests

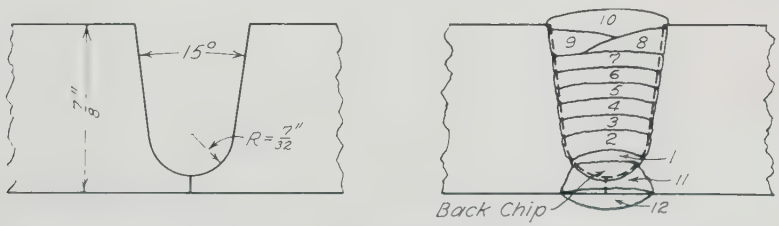


FIG. 4. DETAILS OF WELDING PROCEDURE

TABLE 4

DETAILS OF WELDING PROCEDURE: BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES

Bead No.	Size of Electrode	Amperes†	Volts	Bead No.	Size of Electrode	Amperes	Volts
1	3/16 in.*	170	30	7	3/16 in.	180	30
2	3/16 in.	170	30	8	3/16 in.	180	30
3	3/16 in.	180	30	9	3/16 in.	180	30
4	3/16 in.	180	30	10	3/16 in.	170	30
5	3/16 in.	180	30	11	3/16 in.	180	30
6	3/16 in.	180	30	12	3/16 in.	170	30

*Fleetweld No. 5.
†D. C. current, reversed polarity.

TABLE 5

CLASSIFICATION OF WELDS FROM RADIOGRAPHS: 7/8-IN. CARBON-STEEL PLATES

Specimen No.	Rating*	Specimen No.	Rating	Specimen No.	Rating	Specimen No.	Rating
A1	A	H1	B	O1	A	V1	C
A2	A	H2	A	O2	A	V2	A
A3	A	H3	A	O3	A	V3	B
A4	B	I1	B	O4	A	W1	B
B1	A	I2	B	P1	B	W2	B
B2	A	I3	A	P2	B	W3	A
B3	B	I4	A	P3	A	W4	B
C1	A	J1	A	Q1	B	X1	B
C2	A	J2	A	Q2	A	X2	B
C3	B	J3	A	Q3	A	X3	A
C4	B	K1	B	Q4	A	Y1	A
D1	B	K2	B	R1	B	Y2	B
D2	B	K3	A	R2	A	Y3	A
D3	B	K4	A	R3	B	Y4	A
E1	A	L1	A	S1	A	Z1-1	A
E2	A	L2	A	S2	B	Z1-2	A
E3	B	L3	B	S3	A	Z1-3	A
E4	B	M1	B	S4	A	Z2-1	A
F1	A	M2	B	T1	A	Z2-2	A
F2	D	M3	C	T2	A	Z2-3	B
F3	B	M4	B	T3	B		
G1	A	N1	C	U1	B		
G2	A	N2	B	U2	B		
G3	A	N3	B	U3	A		
G4	A			U4	B		

*Class A rating—applies to welds for which the radiograph showed no flaws.
Class B rating—applies to welds having a trace of porosity.
Class C rating—applies to welds which had a little porosity.
Class D rating—applies to F2 for which the radiograph showed considerable porosity. F2 was the only weld tested that was given a D rating.

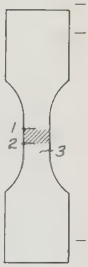
of riveted joints that failed in the plate* indicated that the fatigue strength of the plates with severe stress raisers in the form of rivet holes was almost the same for carbon steel having a static strength of 63 600 lb. per sq. in., as it was for silicon steel having a strength of 80 200 lb. per sq. in. and for nickel steel having a strength of 99 000 lb. per sq. in. It is reasonable to suppose, therefore, that the fatigue strength of butt welds with a severe stress raiser due to a change in

*Univ. of Ill. Eng. Exp. Sta. Bul. 302, page 103.

TABLE 6

STRENGTH OF BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES IN THE AS-WELDED CONDITION

Spec. No.	Plate No.	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, n, in 1000's	Strength in 1000's of lb. per sq. in.			Location of Fatigue Crack
				Static †	Fatigue, F *		
					N=100 000	N=2 000 000	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Cycle: Tension to an Equal Compression							
C1	1	+20.0 to -20.0	167.9	63.8	21.4	14.5 •	1
C2	1	+20.0 to -20.0	251.9	63.8	22.6	15.3 •	1
C3	1	+20.0 to -20.0	271.5	63.8	22.8	15.4 •	2
					Av. 22.3	Av. 15.1 •	
C4	1	+16.0 to -16.0	753.6	63.8	20.8 •	14.1	1
D1	2	+16.0 to -16.0	1795.8	58.2	23.3 •	15.8	1
D2	2	+16.0 to -16.0	947.2	58.2	21.4 •	14.5	3
D3	2	+16.0 to -16.0	473.6	58.2	19.6 •	13.3	2
					Av. 21.3 •	Av. 14.4	
Cycle: 0 to Tension							
K1	1	0 to 30.0	253.2	63.1	33.9	22.9 •	3
K2	1	0 to 30.0	241.7	63.1	33.7	22.8 •	1
K3	1	0 to 30.0	190.9	63.1	32.6	22.2 •	2
K4	1	0 to 28.0	277.1	63.1	32.0	21.7 •	2
					Av. 33.1	Av. 22.4 •	
L1	2	0 to 25.0	1114.4	58.2	34.1 •	23.2	1&3
L2	2	0 to 25.0	763.4	58.2	32.6 •	22.1	3
L3	2	0 to 25.0	816.0	58.2	32.8 •	22.3	3
					Av. 33.2 •	Av. 22.5	
Cycle: Tension to Tension ½ as Great							
S1	1	+22.0 to +44.0	442.0	63.2	53.4	36.2 •	2
S2	1	+22.0 to +44.0	485.0	63.2	54.0	36.6 •	2
S3	1	+22.0 to +44.0	388.0	63.2	52.5	35.5 •	1
					Av. 53.3	Av. 36.1 •	
S4	1	+19.0 to +38.0	1180.7	63.2	52.4 •	35.5	1
T1	2	+19.0 to +38.0	2314.2	58.2	56.0+•	38.0+	1
T2	2	+19.0 to +38.0	2471.1	58.2	56.0+•	38.0+	1&2
T3	2	+19.0 to +38.0	1421.6	58.2	53.7 •	36.4	1
					Av. 54.6 •	Av. 36.9	



$*F = S\left(\frac{n}{N}\right)^{0.13}$

†Strength of adjacent coupons. See Fig. 3 and Table 2.

section at the edge of the reinforcement was not greatly affected by the small difference between the strengths of plates 1 and 2.

The results of the individual tests reported in Tables 6 and 7 are plotted in Fig. 5. It is to be noted that, for a given stress cycle, the number of cycles for failure was different for different specimens. For example, specimens I1, I2, I3, and I4 of Table 7 were all tested on a cycle in which the stress varied from 0 to 30 000 lb. per sq. in., and the number of cycles for failure varied from 140 200 for I2 to 796 300 for I3. Although this is an extreme case, considerable variation in the

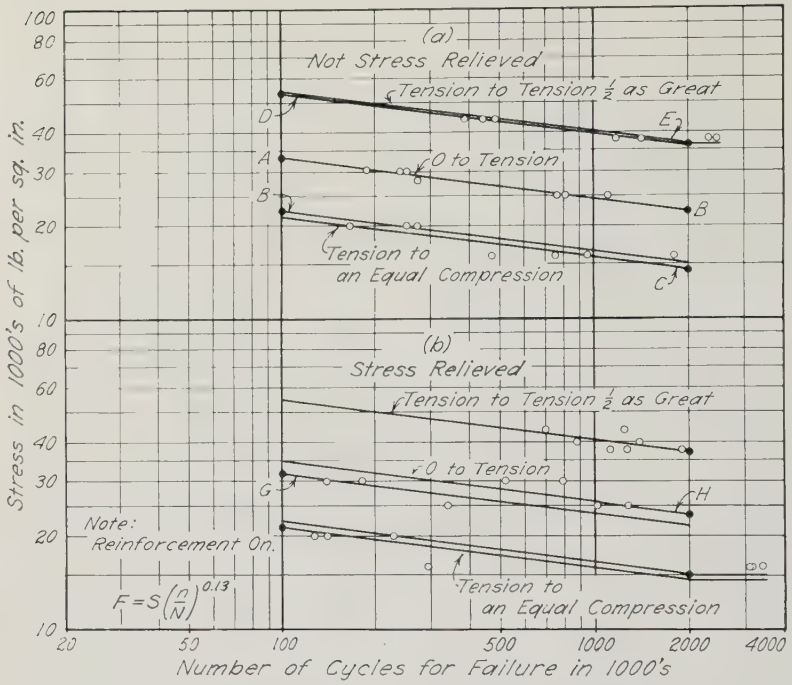


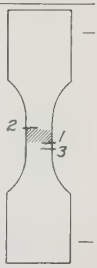
Fig. 5. *S-N* Diagrams for Butt Welds in ⅞-in. Carbon-Steel Plates. Reinforcement On

number of cycles for failure of large fabricated specimens may be expected and the six or seven tests that constituted a series in this investigation were not always enough to adequately determine the *S-N* diagrams. It should be noted, however, that a considerable variation in the number of cycles for failure corresponds to a relatively small variation in the fatigue strength expressed in lb. per sq. in. As previously stated, *S-N* diagrams can be expressed by the equation $F = S(n/N)^K$, an equation that is not of unlimited extension. It seems reasonable to assume that K depends upon the character of the stress raiser and upon the kind of material, and that it has approximately the same value for all specimens made of the same material and with the same stress raisers. A study of the tests reported in Tables 6 to 12, inclusive, indicated that, for specimens made of ⅞-in. carbon-steel plates connected by a butt weld with the reinforcement on, a value of $K = 0.13$ is in fair agreement with the experimental data, whereas, for specimens without welds or with welds planed flush

TABLE 7

STRENGTH OF BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES. REINFORCEMENT ON STRESS-RELIEVED

Spec. No.	Plate No.	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, n, in 1000's	Strength in 1000's of lb. per sq. in.			Location of Fatigue Crack
				Static	Fatigue, F*		
					N=100 000	N=2000000	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Cycle: Tension to an Equal Compression							
A1	1	+20.0 to -20.0	139.6	65.8	20.9	14.2 •	1
A2	1	+20.0 to -20.0	127.5	65.8	20.6	14.0 •	1
A4	1	+20.0 to -20.0	222.9	65.8	22.2	15.0 •	2
					Av. 21.3	Av. 14.4 •	
A3	1	+16.0 to -16.0	3433.1	65.8	23.6+•	16.0+	1
B1	2	+16.0 to -16.0	3152.7	58.8	23.6+ •	16.0+	No Failure
B2	2	+16.0 to -16.0	295.1	58.8	18.4 •	12.5	2
B3	2	+16.0 to -16.0	3145.2	58.8	23.6+•	16.0+	3
					Av. 22.3 •	Av. 15.1	
Cycle: 0 to Tension							
I1	1	0 to 30.0	182.7	62.3	32.4	22.0 •	1
I2	1	0 to 30.0	140.2	62.3	31.4	21.2 •	1
					Av. 31.9	Av. 21.6 •	
I3	1	0 to 30.0	796.3	62.3	39.3 •	26.6	1
I4	1	0 to 30.0	526.5	62.3	37.2 •	25.2	2
J1	2	0 to 25.0	1292.7	58.8	34.9 •	23.6	1
J2	2	0 to 25.0	341.0	58.8	29.3 •	19.9	1
J3	2	0 to 25.0	1034.8	58.8	33.9 •	23.0	1
					Av. 34.9 •	Av. 23.7	
Cycle: Tension to Tension ½ as Great							
Q1	1	+20.0 to +40.0	891.1	63.1	53.2 •	36.0	1
Q2	1	+20.0 to +40.0	1400.0	63.1	56.4 •	38.4	1
Q3	1	+22.0 to +44.0	700.0	63.1	56.7 •	38.4	2
					Av. 55.4 •	Av. 37.5	
Q4	1	+22.0 to +44.0	1248.9	63.1	61.1 •	41.4	2
R1	2	+19.0 to +38.0	1278.9	58.8	52.9 •	35.9	2
R2	2	+19.0 to +38.0	1130.1	58.8	52.1 •	35.3	1
R3	2	+19.0 to +38.0	1914.8	58.8	55.8 •	37.8	2
					Av. 55.5 •	Av. 37.6	



$*F = S\left(\frac{n}{N}\right)^{0.13}$

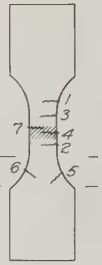
with the base plate, the value of K is of the order of 0.18.* These values of K were used in computing the values of F given in columns 6 and 7 of Tables 6 to 12, inclusive, and in drawing the S-N diagrams of Figs. 5 to 7, inclusive. The small open circles of the S-N diagrams

*The exponent K was assigned a value of 0.10 in the presentation of the fatigue tests of riveted joints, Bulletin 302 of the University of Illinois Engineering Experiment Station. The same value was used in presenting the results of some of the fatigue tests of welded joints in Bulletin 310 and in the Journal of the American Welding Society, No. 3, Vol. 19, p. 100 S. A comparison of the values of F in Table 6 with corresponding values in Table 2 of the article in the Journal of the American Welding Society indicates that changing K from 0.10 to 0.13 changed $F_{100\,000}$ from 21 600 lb. per sq. in. to 22 400 lb. per sq. in., these values being the average from tests C1, C2, and C3, in each instance. A comparison of other similar values not marked with a small circle indicates that changing K from 0.10 to 0.13 changed the average value of F about 3 per cent for the tests reported in Table 6, the change for any individual test depending upon the value of n/N.

TABLE 8

STRENGTH OF BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES. REINFORCEMENT MACHINED OFF. NOT STRESS-RELIEVED

Spec. No.	Plate No.	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, n, in 1000's	Strength in 1000's of lb. per sq. in.			Location of Fatigue Crack
				Static	Fatigue, F*		
					N=100 000	N=2 000 000	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Cycle: Tension to an Equal Compression							
G1	1	+30.0 to -30.0	54.7	63.8	26.9	15.7 •	1
G2	1	+30.0 to -30.0	89.1	63.8	29.4	17.1 •	2
G3	1	+30.0 to -30.0	106.8	63.8	30.4	17.7 •	3
G4	1	+22.0 to -22.0	558.9	63.8	30.0	17.5 •	1&6
					Av. 29.2	Av. 17.0 •	
H1	2	+24.0 to -24.0	276.2	57.2	28.8	16.8 •	1
H2	2	+24.0 to -24.0	370.5	57.2	30.4	17.7 •	1
H3	2	+24.0 to -24.0	175.5	57.2	26.6	15.5 •	5
					Av. 28.6	Av. 16.7 •	
Cycle: 0 to Tension							
O1	1	0 to 45.0	104.9	63.1	45.4	26.5 •	4
O2	1	0 to 45.0	223.2	63.1	52.2	30.4 •	5
O3	1	0 to 45.0	155.3	63.1	48.7	28.4 •	5
					Av. 48.8	Av. 28.4 •	
O4	1	0 to 32.0	3540.4	63.1	54.9+ •	32.0+	No Failure
P1	2	0 to 35.0	334.6	57.2	43.5 •	25.4	4
P2	2	0 to 33.0	607.4	57.2	45.7 •	26.6	4
P3	2	0 to 33.0	1081.7	57.2	50.7 •	29.5	4
					Av. 48.7 •	Av. 28.4	
Cycle: Tension to Tension ½ as Great							
W1	1	+22.5 to +45.0	1526.4	63.2	—	42.9	7
W2	1	+22.5 to +45.0	2166.2	63.2	—	45.0+	2
W3	1	+22.5 to +45.0	1603.0	63.2	—	43.2	7
						Av. 43.7	



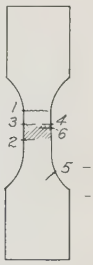
*$F = S\left(\frac{n}{N}\right)^{0.18}$

represent the experimental data in columns 3 and 4 of the tables. The position of the S-N diagram was determined in the following manner. Because the equation is empirical, its accuracy decreases with the degree of extrapolation that is used. For this reason, only tests K1, K2, K3, and K4 of Table 6 were considered in locating point A of the line AB, Fig. 5, and the ordinate of A, 33 100 lb. per sq. in., is the average of the fatigue strengths from these tests. Likewise only tests L1, L2, and L3 were considered in locating point B, whose ordinate, 22 500 lb. per sq. in., is the average of the fatigue strengths from these tests also. A line, $F = S\,(n/N)^{0.13}$, was then drawn through A and a second line with the same equation was drawn through B. In this instance the two lines coincide, indicating that the procedure followed gave excellent results for this group of tests for which the individual tests were very consistent with each other. Lines B and C were constructed in the manner described but they do not quite coin-

TABLE 9

STRENGTH OF BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES. REINFORCEMENT MACHINED OFF. STRESS-RELIEVED

Spec. No.	Plate No.	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, n, in 1000's	Strength in 1000's of lb. per sq. in.			Location of Fatigue Crack
				Static	Fatigue, F*		
					N=100 000	N=2 000 000	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Cycle: Tension to an Equal Compression							
E1	1	+30.0 to -30.0	121.5	65.8	31.1	18.1 •	5
E2	1	+30.0 to -30.0	26.9	65.8	23.7	13.8 •	3
E3	1	+30.0 to -30.0	24.6	65.8	23.3	13.6 •	3
F1	2	+24.0 to -24.0	125.4	60.0	25.0	14.6 •	2
F2	2	+24.0 to -24.0	58.0	60.0	21.8	12.7 •	1 †
F3	2	+24.0 to -24.0	50.8	60.0	21.2	12.4 •	1 †
M4	1	+20.0 to -20.0	370.5	62.3	25.3	14.8 •	6
					Av. 24.5	Av. 14.3 •	
E4	1	+20.0 to -20.0	710.2	65.8	28.5 •	16.6	1
V2	2	+20.0 to -20.0	719.1	60.0	28.5 •	16.6	5
					Av. 28.5 •	Av. 16.6	
Cycle: 0 to Tension							
M1	1	0 to 45.0	198.6	62.3	50.9	29.7 •	3&4
M2	1	0 to 45.0	173.2	62.3	49.7	29.0 •	2
M3	1	0 to 45.0	136.1	62.3	47.6	27.7 •	3&4
					Av. 49.4	Av. 28.8 •	
N1	2	0 to 36.0	342.6	61.1	44.9 •	26.2	5
N2	2	0 to 36.0	505.3	61.1	48.2 •	28.1	5
N3	2	0 to 35.0	619.2	61.1	50.0 •	29.2	5
					Av. 47.7 •	Av. 27.8	
Cycle: Tension to Tension ½ as Great							
U1	1	+22.5 to +45.0	1175.3	63.1	—	40.9	5
U2	1	+22.5 to +45.0	1511.2	63.1	—	42.8	6
V1	2	+22.5 to +45.0	1757.5	61.1	—	44.0	2
						Av. 42.6	



$^{*}F = S\left(\frac{n}{N}\right)^{0.18}$

† Specimen had surface injury at point of failure.

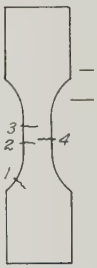
cide, although they lie fairly close together. The same statement is true for lines D and E. The lines G and H, Fig. 5, are separated by an appreciable distance. Moreover, tests of the group which they represent are quite scattered, so that it was difficult to draw a line satisfactorily from these tests alone. If, however, the family relationship expressed by K may be assumed to exist, it will be helpful in arriving at the most probable interpretation of this group of tests that are mutually somewhat inconsistent, providing, as in this instance, enough specimens with the same characteristics were tested to establish the value of K. All of the S-N diagrams on Figs. 5 to 7, inclusive, have been constructed in the manner described.

The S-N diagram for small machined specimens, when plotted on a logarithmic field, consists of two parts: a straight line sloping down-

TABLE 10

STRENGTH OF BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES. REINFORCEMENT GROUND OFF. NOT STRESS-RELIEVED

Spec. No.	Plate No.	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, n, in 1000's	Strength in 1000's of lb. per sq. in.			Location of Fatigue Crack
				Static	Fatigue, F *		
					N=100 000	N=2 000 000	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Cycle: Tension to an Equal Compression							
Y1	2	+30.0 to -30.0	38.4	60.2	25.3	14.7 •	2
Y2	2	+30.0 to -30.0	78.5	60.2	28.7	16.8 •	1
Y3	2	+30.0 to -30.0	49.7	60.2	26.5	15.4 •	2
					Av. 26.8	Av. 15.6 •	
Cycle: 0 to Tension							
Y4	2	0 to +45.0	197.3	60.2	50.9	29.7 •	3
Z1-1	2	0 to +45.0	218.2	57.7	51.8	30.2 •	2
Z1-2	2	0 to +31.0	273.0	57.7	37.1	21.7 •	3
Z1-3	2	0 to +45.0	107.4	57.7	45.6	26.5 •	4
Z2-2	2	0 to +32.0	231.4	57.7	37.2	21.7 •	4
					Av. 44.5	Av. 26.0 •	
Z2-1	2	0 to +32.0	728.1	57.7	45.8 •	26.7	3
Z2-3	2	0 to +32.0	604.7	57.7	44.2 •	25.8	4
					Av. 45.0 •	Av. 26.3	



$*F = S\left(\frac{n}{N}\right)^{0.18}$

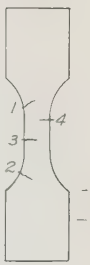
ward to the right and a horizontal line, the two lines being connected by a short curve. The ordinate of the horizontal line has been considered as representing the endurance limit of the specimen.

The endurance limit determined in this manner may be defined as the greatest stress to which the specimen can be subjected an infinite number of times without failure. This endurance limit has different values for various materials and various types of specimens. The structural engineer is interested primarily in a fatigue strength based upon failure at a finite number of cycles. A somewhat limited experience with structural steel in the form of specimens with large stress raisers indicated that if a specimen withstood 2 000 000 to 3 000 000 cycles it was not likely to fail except at a much greater number of cycles. If the equation $F = S\,(n/N)^{0.13}$ were applicable up to values of n equal to 4 000 000, the values of the fatigue strength computed by that equation would be only 9 per cent greater if failure due to a given stress cycle took place at 4 000 000 cycles than it would have been if failure due to the same stress cycle had taken place at 2 000 000 cycles. In view of these facts and considering that the curve joining the two straight portions of the S-N diagrams appears to be in the vicinity representing a value of n equal to 2 000 000, the following practice was followed in reporting the results of fatigue tests.

TABLE 11

STRENGTH OF BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES WITHOUT WELDS BUT WITH MILL SCALE ON

Spec. No.	Plate No.	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, n, in 1000's	Strength in 1000's of lb. per sq. in.			Location of Fatigue Crack
				Static	Fatigue, F *		
					N=100 000	N=2 000 000	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Cycle: Tension to an Equal Compression							
GG1	1	+30.0 to -30.0	57.9	64.8	27.2	16.2 •	3
GG2	1	+30.0 to -30.0	58.6	64.8	27.3	16.3 •	1
GG3	1	+30.0 to -30.0	75.5	64.8	28.5	16.6 •	3
					Av. 27.7	Av. 16.4 •	
GG4	1	+20.0 to -20.0	1709.1	64.8	33.3 •	19.4	1
HH1	2	+22.0 to -22.0	655.1	59.4	30.9 •	18.0	1
HH2	2	+21.0 to -21.0	559.7	59.4	28.6 •	16.7	1
HH3	2	+21.0 to -21.0	273.0	59.4	25.8 •	14.7	1
HH4	2	+20.0 to -20.0	761.9	59.4	28.8 •	16.8	1
					Av. 29.5 •	Av. 17.1	
Cycle: 0 to Tension							
001	1	0 to 45.0	155.4	62.7	48.7	28.4 •	1
002	1	0 to 45.0	187.3	62.7	50.4	29.4 •	2
003	1	0 to 45.0	184.7	62.7	50.3	29.3 •	2
					Av. 49.8	Av. 29.0 •	
PP1	2	0 to 38.0	1377.8	58.6	60.9 •	35.5	2
PP2	2	0 to 32.0	3089.2	58.6	54.6 •	32.0+	No Failure
PP3	2	0 to 32.0	901.2	58.6	47.5 •	27.7	4
HH5	2	0 to 31.0	3004.6	63.1	52.9+ •	31.0+	No Failure
					Av. 54.0 •	Av. 31.6	
Cycle: Tension to Tension ½ as Great							
WW1	1	+25.0 to +50.0	2203.8	63.2		50.0+	No Failure
XX1	2	+20.5 to +41.0	3263.8	58.5		41.0+	No Failure
XX2	2	+22.5 to +45.0	4252.9	58.5		45.0+	No Failure
XX3	2	+20.0 to +40.0	3459.3	58.5		40.0+	No Failure
						Av. 50.0 (Probable Value)	



* $F = S\left(\frac{n}{N}\right)^{0.18}$

If failure did not occur at 2 000 000 cycles, the actual stress used in the test was reported for the value of $F_{2\ 000\ 000}$, and the numerical value was followed by a plus (+) sign, indicating that the fatigue strength was equal to and possibly a little greater than the value reported. This method was not entirely satisfactory, but no better method could be devised, and the fact that the fatigue strength equaled or exceeded a certain stress has a distinct value. Of course, if the stress used in the test was very much less than the true value of $F_{2\ 000\ 000}$, the values reported would be very much in error. This was true for the plain plates without welds tested on a cycle in which the stress varied from tension to tension one-half as great but, for these,

TABLE 12

STRENGTH OF BUTT WELDS IN ⅞-IN. CARBON-STEEL PLATES. REINFORCEMENT AND MILL SCALE PLANED OFF

Spec. No.	Plate No.	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles‡ for Failure, n, in 1000's	Strength in 1000's of lb. per sq. in.			Location of Fatigue Crack
				Static	Fatigue, F*		
					N=100 000	N=2 000 000	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Butt Welded							
U3†	1	0 to +47.0	182.8	63.1	52.4	30.6 •	3
U4†	1	0 to +47.0	223.7	63.1	54.3	31.7 •	1
X2	2	0 to +47.0	251.3	58.6	54.0	31.5 •	4
X3	2	0 to +47.0	238.9	58.6	54.9	32.1 •	5
					Av. 53.9	Av. 31.5 •	
Plain Plates Without Welds							
WW2	1	0 to +47.0	417.9	63.1	60.8	35.5 •	5&6
WW3	1	0 to +47.0	330.0	63.1	58.3	34.0 •	1
					Av 59.6	Av. 34.8 •	

*$F = S\left(\frac{n}{N}\right)^{0.18}$

†Specimens U3 and U4 were stress relieved by heat treatment. Others were not.

‡Cycle was 0 to tension for all specimens.

the tests established the fact that the fatigue strength exceeded the yield point of the material so that its exact value had only academic interest.

5. *Discussion of Results.*—The results of fatigue tests of butt welds in ⅞-in. carbon-steel plates reported in this bulletin were somewhat erratic, but this was not surprising considering the character of the joints. It is well known that any surface irregularity in a specimen is a stress raiser that reduces the fatigue strength. A sharp reentrant angle at the edge of the reinforcement produces a greater concentration of stress than would be produced if the reinforcement were connected to the base plate by curved surfaces. Any slight undercutting at the edge of the reinforcement, internal flaws in the weld, or indentation in the surface of the plate, would also cause a concentration of stress. In view of these facts, a study was made to determine whether there was any correlation between erratic results of the fatigue tests and unusual geometric characteristics of the specimens.

In the study to determine the effect of flaws in welds upon their fatigue strength, the radiograph rating and the fatigue-strength rating were compared. The radiograph rating of all welds is given in Table 5. The fatigue-strength rating of a specimen was taken as the ratio of the fatigue strength of that specimen to the average fatigue strength of the group of specimens to which it belonged.

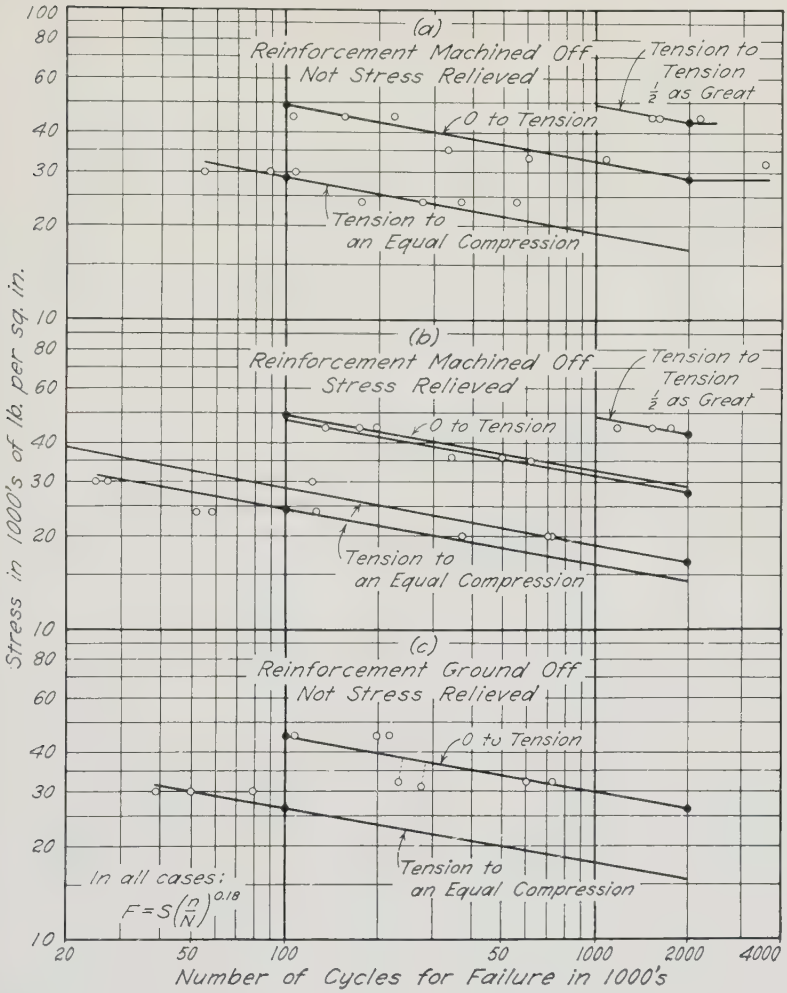


FIG. 6. *S-N* DIAGRAMS FOR BUTT WELDS IN ⅞-IN. CARBON-STEEL PLATES. REINFORCEMENT OFF

For example, the fatigue strength of C1, Table 6, was 21 400 lb. per sq. in., and the average for the group consisting of C1, C2, and C3 was 22 300 lb. per sq. in. The fatigue-strength rating was, therefore, $\frac{21.4}{22.3} = 0.96$. The fatigue-strength rating of all specimens with welds was determined in this manner, and the radiograph rating and the fatigue-strength rating for all specimens with the rein-

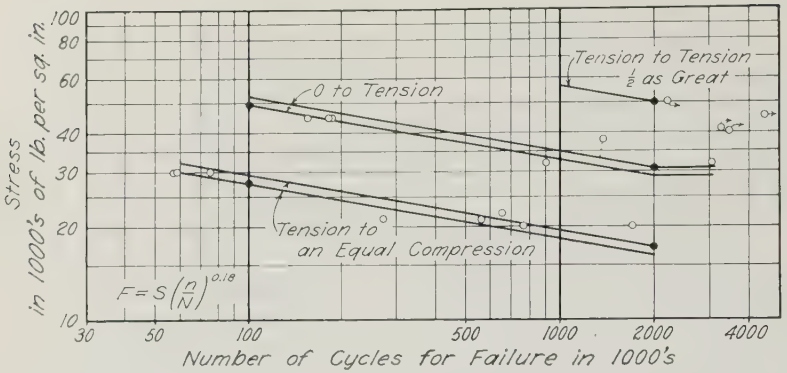


Fig. 7. *S-N* Diagrams for Butt Welds in ⅞-in. Carbon-Steel Plates Without Welds but With Mill Scale On

forcement on were compared in Table 13. Specimens with a radiograph rating of A are at the left and those with rating of B are at the right. There were no specimens tested with the reinforcement on that had either a C or a D rating. The specimens having a radiograph rating of A had an average fatigue-strength rating of 0.997, and those having a radiograph rating of B had an average fatigue-strength rating of 1.005. It is apparent that flaws characterized by the radiograph rating B did not have an appreciable effect upon the fatigue strength of the butt welds with the reinforcement on. This might have

Table 13

Relation Between Radiograph Rating and Fatigue-Strength Rating for Specimens With Reinforcement On

Radiograph Rating A				Radiograph Rating B			
Specimen No.	Fatigue-Strength Rating	Specimen No.	Fatigue-Strength Rating	Specimen No.	Fatigue-Strength Rating	Specimen No.	Fatigue-Strength Rating
A1	0.98	C1	0.96	A4	1.04	K2	1.02
A2	0.97	C2	1.01	I1	1.02	S2	1.01
A3	1.06	K3	0.98	I2	0.98	D1	1.10
I3	1.13	K4	0.97	Q1	0.96	D2	1.01
I4	1.07	S1	1.00	B3	1.06	D3	0.92
Q2	1.02	S3	0.98	R1	0.96	L3	0.99
Q3	1.02	S4	0.96	R3	1.01	T3	0.99
Q4	1.10	L1	1.03	C3	1.02		
B1	1.06	L2	0.98	C4	0.98	Av.	1.005
B2	0.83	T1	1.03	K1	1.02		
J1	1.00	T2	1.03				
J2	0.84						
J3	0.97	Av.	0.997				
R2	0.94						

TABLE 14
RELATION BETWEEN RADIOGRAPH RATING AND FATIGUE-STRENGTH RATING FOR SPECIMENS WITH REINFORCEMENT MACHINED OFF

Radiograph Rating A		Radiograph Rating B		Radiograph Rating C	
Specimen No.	Fatigue-Strength Rating	Specimen No.	Fatigue-Strength Rating	Specimen No.	Fatigue-Strength Rating
O1	0.93	P1	0.89	M3	0.96
P3	1.04	P2	0.94	V1	1.03
W3	0.99	W1	0.98		
E2	0.97	E3	0.95		
F1	1.02	M4	1.03		
U3	0.97	M1	1.03		
X2	1.00	U1	0.96		
		U2	1.00		
		M2	1.00		
Av.	0.988	Av.	0.975	Av.	0.995

been expected since the change in section at the edge of the reinforcement was so much more effective as a stress raiser than minor flaws in the welds that the latter would have no effect upon the fatigue strength of the joint.

The radiograph rating and the fatigue-strength rating for specimens with the reinforcement machined off are compared in Table 14. Only those specimens that broke either in the weld or at the edge of the weld were included in this table because the effect of the flaws in the weld could not be evaluated if the specimen broke outside of the weld. The seven specimens with a radiograph rating of A that broke at the weld had an average fatigue-strength rating of 0.988; the nine specimens with a radiograph rating of B that broke at the weld had an average fatigue-strength rating of 0.975; the two with a radiograph rating of C that broke at the weld had an average fatigue-strength rating of 0.995. Specimen F2, the only one with the reinforcement off that had a radiograph rating of D, broke outside of the weld, but, as noted in Table 9, failure occurred at a severe surface injury and the effect of the flaws in the weld was not disclosed. It is apparent that, for the specimens tested, those having a radiograph rating of B or C had as great a fatigue strength as those having a radiograph rating of A. However, the fatigue strength was about 8 per cent greater for the specimens that broke outside of the weld than for those that broke in the weld.

The tests reported in Tables 8 and 9 indicated that specimens with the reinforcement machined flush with the base plate had a much greater fatigue strength than specimens with the reinforcement on. In

FIG. 8. SPECIMEN Y4 WITH FATIGUE CRACKS FOLLOWING TRANSVERSE SCRATCHES DUE TO GRINDING

general, it is not practicable to machine the welds of structural joints, and a series of tests was made to determine whether grinding the reinforcement off with a portable grinder would prove as beneficial as machining it off. There were ten specimens tested in this series and the results are presented in Table 10. The fatigue strength was much greater for the specimens with the reinforcement ground off than it was for the specimens with the reinforcement on, but it was not quite as great as it was for the specimens with the reinforcement machined off. The fatigue strength of the specimens with the reinforcement ground off was quite erratic, the fatigue-strength rating being 0.83 and 0.84 for Z1-2 and Z2-2 and 1.16 for Z1-1. All three of these specimens had a radiograph rating of A. The low fatigue strength of Z1-2 and Z2-2 may have been due to a single large stress raiser that resulted in a large area of progressive fracture, sometimes designated as a "fisheye," as shown in Fig. 12 and discussed on page 37.

Specimen Y4 was ground so as to leave scratches transverse to the direction of stress and three fatigue cracks developed simultaneously as shown in Fig. 8. The fatigue-strength rating for this specimen was 1.14, and the radiograph rating was A.

The specimens with the reinforcement and mill scale machined off and the surfaces polished were the ones for which the fatigue strength was most likely to be reduced by the flaws in the welds because they had no surface irregularities to act as stress raisers. There were only

four of these specimens tested, and the results, while of interest, cannot, because of the small number, be considered as conclusive. These specimens were U3, U4, X2, and X3, all shown in Table 12. The radiograph rating was A for specimens U3 and X2 and B for U4 and X3. The two with an A rating both broke in the weld and had an average fatigue-strength rating of 0.985; the two with a B rating both broke outside of the weld and had an average fatigue-strength rating of 1.015. It should be noted, however, that the plates without joints and with the mill scale machined off and the surfaces polished had a fatigue strength 10 per cent greater than that of similar specimens with welds.

It is apparent from the foregoing discussion that flaws in welds designated by a radiograph rating of B did not affect the fatigue strength of the weld. The flaws designated by a radiograph rating of C did not have an appreciable effect upon the fatigue strength, but the number of tests was too small for the evidence to be conclusive.

The ends of the specimens were made wider than the central portion, as shown in Fig. 1, in order that they might be attached to the pulling heads of the testing machine. The transition curve connecting the narrow to the wide portion was a circular arc with a 9-in. radius. Moreover, the edges were carefully machined and polished and the cylindrical surface was tangent to the plane edges of the narrow portion. In spite of this large radius and careful machine work, many of the specimens without welds and welded specimens with the reinforcement off failed in the fillet, usually at the junction of the fillet and the middle portion. It is known that a fillet, even with a large radius, is a stress raiser. Studies of plastic models with polarized light* indicated a stress at the edge of the specimen at the junction of the fillet approximately 15 per cent greater than the average over the section. The data in Table 11 indicate that of the 13 specimens without welds that failed, 10 failed at a fillet and 3 failed in the central portion away from the fillets. Likewise, of the 34 welded specimens with the reinforcement off reported in Tables 8 and 9, 17 broke at the junction with a fillet and 6 broke between the fillet and the weld. But the data given in Tables 8, 9, and 11 indicate that there was no significant difference in the fatigue strength between the specimens that broke in the fillet and those that broke between the fillets and the weld. Therefore it would appear that, while the stress-raising effect of the fillet caused a large number of the specimens to fail at the end of the fillet, the fatigue strength of the central portion of the specimen,

*These tests were made by T. J. Dolan, Assistant Professor of Theoretical and Applied Mechanics, University of Illinois.

TABLE 15

RELATION BETWEEN REINFORCEMENT RATING AND FATIGUE-STRENGTH RATING OF BUTT WELDS IN ⅞-IN. CARBON-STEEL PLATES

Reinforcement Rating							
A		B		C		D	
Specimen No.	Fatigue-Strength Rating	Specimen No.	Fatigue-Strength Rating	Specimen No.	Fatigue-Strength Rating	Specimen No.	Fatigue-Strength Rating
D1	1.09	B3	1.06	A1	0.98	R1	0.96
I4	1.07	C1	0.96	A3	1.04	R2	0.94
T2	1.03	D2	1.00	C3	1.02		
		J3	0.97	C2	1.01	Av.	0.95
Av.	1.063	K1	1.03	C4	0.98		
		K4	0.97	J1	1.00		
		L1	1.03	K3	0.98		
		Q2	1.02	L3	0.99		
		S4	0.96	I1	1.02		
		T1	1.03	I2	0.98		
		T3	0.98	Q4	1.10		
				Q1	0.96		
		Av.	1.001	S1	1.00		
				S2	1.01		
				Av.	1.005		

although slightly greater, was not significantly greater than the values reported in the tables.

The fatigue strength of the welded specimens was much greater for those with the reinforcement off than for those with the reinforcement on, indicating clearly that the change in section at the edge of the reinforcement acted as a serious stress raiser. It was reasonable to suppose, therefore, that the profile of the reinforcement might affect its action as a stress raiser. A study was made to determine whether or not there was any correlation between the profile of the reinforcement and the fatigue strength of the specimen. Specimens for which the reinforcement flowed by a relatively smooth concave surface into the base plate were given an A rating. Specimens for which the reinforcement was high and rough and joined the base plate with a sharply re-entrant angle were given a D rating. The remaining specimens were given either a B or a C rating, depending upon the height of the reinforcement and the sharpness of the angle at its edge, but for all of the B and C specimens there was a re-entrant angle at the edge of the reinforcement. The relation between the reinforcement rating and the fatigue-strength rating is given in Table 15. There were only three specimens that were given a reinforcement rating of A, but they all had a fatigue-strength rating above unity and an average rating of 1.063. There were only two specimens that

TABLE 16

EFFECT OF ECCENTRICITY OF LOAD UPON FATIGUE STRENGTH OF SPECIMEN: ¾-IN. CARBON-STEEL PLATE WITHOUT WELD BUT WITH MILL SCALE ON BOTH SIDES

P/A for the stress cycle varied from 24 000 lb. per sq. in. tension to an equal compression for all tests

Specimen No.	Eccentricity in.	Number of Cycles for Failure	$F_{200\,000} = 24\,000 \left(\frac{n}{200\,000}\right)^{0.18}$
2	None	185 700	23 680
3	None	296 200	25 760
4	None	220 900	24 440
			Av. 24 630
1	⅛	111 400	21 600
5	⅛	297 500	25 780
6	⅛	327 000*	26 220
			Av. 24 530

*See text.

were given a reinforcement rating of D, but they both had a fatigue-strength rating below unity and an average rating of 0.95. There were eleven specimens with a reinforcement rating of B and fourteen with a rating of C, but the average fatigue-strength rating was unity for each group. There is, therefore, a little evidence that it may be possible to distinguish between an unusually good and a definitely bad type of reinforcement, but any more refined rating would seem to be uncertain.

There were 42 welded specimens tested with the reinforcement on. Two had a fatigue-strength rating below 0.85 (0.83 for B2 and 0.84 for J2); all of the others had a fatigue-strength rating of 0.90 or more. The strongest had a rating of 1.13. There were 13 plates without joints but with mill scale on that were tested to failure. The weakest, HH3 and PP3, had fatigue-strength ratings of 0.86 and 0.88, respectively, and the strongest, PP1 and GG4, had fatigue-strength ratings of 1.12 and 1.13, respectively. Considering the number of each kind of specimen involved, it is apparent that the results of the tests were about as consistent for the specimens with welds as for the specimens without welds.

Although care was taken to center the specimens in the fatigue testing machine so as to bring the line of action of the force at mid-width of the specimen, there was always a possibility that the load would be slightly eccentric and produce a flexural as well as an axial stress. Therefore a series of tests was made to study the effect of an eccentricity of load upon the fatigue strength of a plate.

There were six specimens used in this study, each of which consisted of a plate without weld, but with mill scale on both sides. The

TABLE 17

STATIC STRENGTH OF FATIGUE SPECIMENS

Values in upper line are from fatigue-type specimens, those in lower line from standard control specimens

Specimen No.	Parent Plate No.	Type of Specimen	Previous Fatigue Test		Stress 1000 lb. per sq. in.		Reduction of Area per cent	Elongation in 8 in. per cent
			Number of Cycles in 1000s	Stress 1000 lb. per sq. in.	Yield Point	Ultimate		
GGS	1	Plain plate	None		35.4	64.0	43.2	34.1
					36.6	63.1	52.2	28.2
HHS	1	Plain plate	3004.6	0 to +31	37.0	62.6	45.4	34.8
					36.6	63.1	53.7	32.2
WW1	1	Plain plate	2203.8	+25 to +50	56.4	65.1	42.4	26.4
					36.5	63.2	53.1	30.6
PP2	2	Plain plate	3089.2	0 to +32	36.6	58.0	49.0	31.3
					32.3	57.2	56.5	33.6
XX1	2	Plain plate	3263.8	+20.5 to +41.0	46.3	61.8	45.6	31.4
					35.3	58.8	56.5	31.6
XX2	2	Plain plate	4252.9	+22.5 to +45.0	49.5	60.9	45.8	29.2
					32.2	58.2	56.0	30.6
XX3	2	Plain plate	3459.3	+20.0 to +40.0	47.7	59.9	45.0	30.6
					32.2	58.2	56.0	30.6
AS	2	Butt weld, reinf. on, stress-relieved	None		34.4	58.7	46.8	31.6
					31.4	58.2	57.0	30.0
CS	2	Butt weld, reinf. on, not stress-relieved	None		33.6	60.1	44.7	27.4
					35.3	58.8	56.5	31.6
ES	2	Butt weld, reinf. off, stress-relieved	None		36.0	62.9	44.9	31.4
					34.2	62.2	54.5	32.3
GS	2	Butt weld, reinf. off, not stress-relieved	None		31.6	61.0	47.8	30.3
					34.8	60.0	55.5	33.8
B1	2	Butt weld, reinf. on, stress-relieved	3152.7	+16 to −16	35.8	59.8	47.4	31.5
					31.4	58.2	57.0	30.0

specimens were cut from a single 12-in. by ¾-in. carbon-steel plate and had the outline of the specimens detailed in Fig. 1, except that the center portion was off-set ⅛ in. from the centerline of the end holes for the specimens that were to be subjected to an eccentric load. All specimens were tested in the same machine and all were tested on a cycle in which P/A varied from 24 000 lb. per sq. in. tension to 24 000 lb. per sq. in. compression. The eccentricity of the line of action of the force was measured at the beginning of a test and at frequent intervals thereafter. The results of the tests are given in Table 16. The three specimens with a centric load were very consistent; the three with an eccentric load were somewhat inconsistent: specimen 1 broke at a small number and specimen 6 at a large number of cycles. The test for specimen 6 was somewhat irregular. It was normal up to 327 000 cycles, but the machine got out of adjustment sometime between 327 000 and 477 000 cycles, and during at least a portion of that time the load was smaller than it was supposed to be. The load was corrected at 477 000 cycles and the machine remained in adjustment until the specimen failed at 838 000 cycles. The cycles that occurred after the beginning of the period of maladjustment were not included in the total number of cycles for failure given in Table 16.

The fatigue strength for failure at 200 000 cycles was computed for all tests by means of the equation $F_{200\,000} = 24\,000 \left(\frac{n}{200\,000}\right)^{0.18}$ and has been reported in the last column of the table. If test 6 is considered as having ended at 327 000 cycles (it is known to have been normal up to that point) the resulting fatigue strength would be 24 530 lb. per sq. in., and the averages for the two sets of three tests each would have differed by less than one per cent. Inasmuch as the eccentricity was generally kept well below $\frac{1}{16}$ in. for the main series of tests, it is reasonable to believe that the error due to eccentricity was not significant.

6. *Static Tests of Fatigue Specimens.*—Static tests were made on specimens having the same dimensions as the fatigue specimens. The results of these tests are given in Table 17. Two sets of physical properties are given for each specimen; those in the upper line were obtained from the fatigue-type of specimen, and those in the lower line from a standard tension control specimen. A number of specimens that had been tested in fatigue, but without failure, were also subjected to a static test, as noted in the table.

The fatigue-type of specimen that had not been subjected to a fatigue test had approximately the same yield point and ultimate strength as the control specimens cut from the same parent plate, but the reduction in area and elongation in 8 in. differed somewhat for the two types of specimens. The fatigue tests that did not cause failure had very little effect upon the ductility or ultimate strength of the material, as determined by subsequent static tests, but they increased the yield point in those instances for which the maximum stress in the fatigue test exceeded the original yield point of the material. Specimen XX2, after having been subjected to over 4 000 000 cycles in which the stress varied from 45 000 lb. per sq. in. tension to a tension one-half as great, had a reduction of area of 45.8 per cent, an elongation in 8 in. of 29.2 per cent, a yield point of 49 500 lb. per sq. in., and an ultimate strength of 60 900 lb. per sq. in. Specimen WW1, after having been subjected to over 2 200 000 cycles in which the stress varied from 50 000 lb. per sq. in. tension to a tension one-half as great, had a reduction of area of 42.4 per cent, an elongation in 8 in. of 26.4 per cent, a yield point of 56 400 lb. per sq. in., and an ultimate strength of 65 100 lb. per sq. in. The ductility of this steel, after having been subjected to so many applications of a stress exceeding its original yield point, is very gratifying.

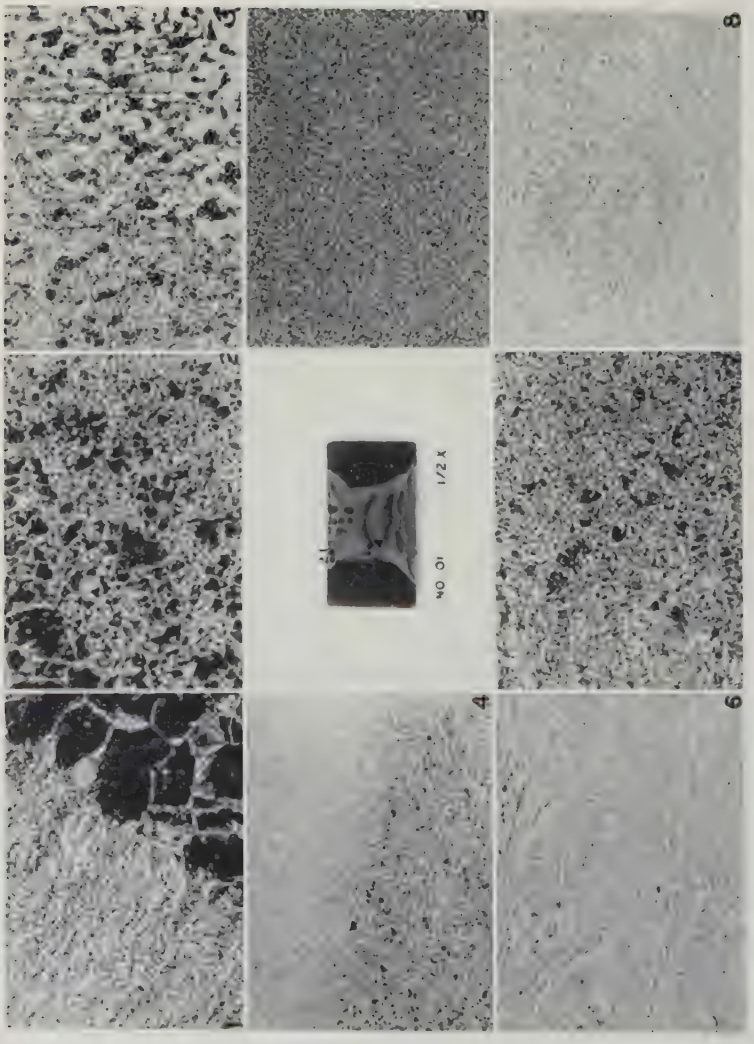


FIG. 9. MICROSTRUCTURE OF WELD, SPECIMEN 01. TYPICAL FOR ALL SPECIMENS OF 7/8-IN. CARBON-STEEL PLATES

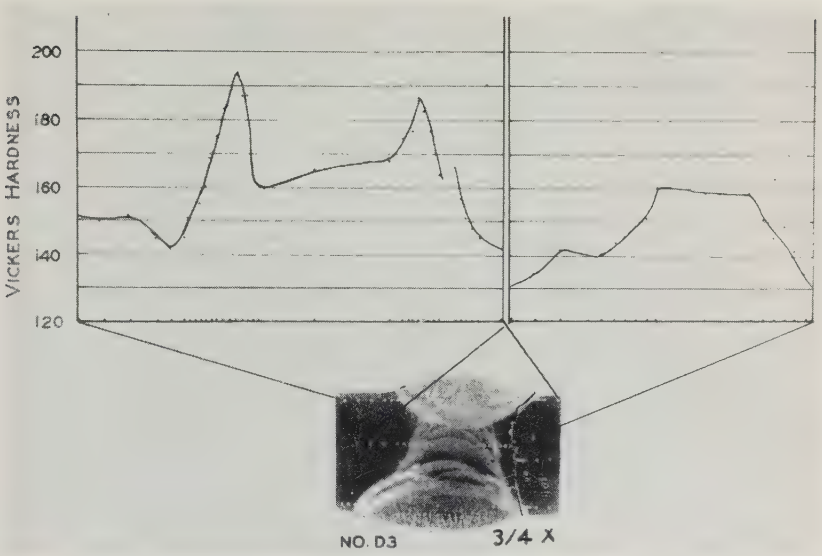


FIG. 10. HARDNESS DIAGRAMS FOR SPECIMEN D3. TYPICAL FOR ALL SPECIMENS OF 7/8-IN. CARBON-STEEL PLATES

7. *Metallurgical Studies.*—Studies were made to determine the microstructure and the hardness variations in the critical zones of the weld. Very little difference was observed in the microstructure of the welds of the various joints. The structure was found to be the same for the two parent plates and also for the welds that were stress-relieved and those that were not. The microstructure of the various regions in the joint of specimen O1, which is typical of the others, is shown in Fig. 9. The area with the very large grains was the hardest of any region in the weld. The structure was sorbitic, however, which indicated high strength and ductility.

The variations in hardness in the vicinity of the weld are shown by the diagrams of Fig. 10. These diagrams were drawn for specimen D3, but are representative of all of the specimens. The maximum hardness in the heat-affected zone varied from 185 to 217 Vickers hardness numbers, values well within the range of acceptable hardness for welded joints.

The character of some of the fractures is of interest. The reinforcement had been planed off specimen O1, and the fracture was in the weld metal, as shown in Fig. 11*G*. The fatigue crack started at some small discontinuities, such as blow holes or inclusions, in the

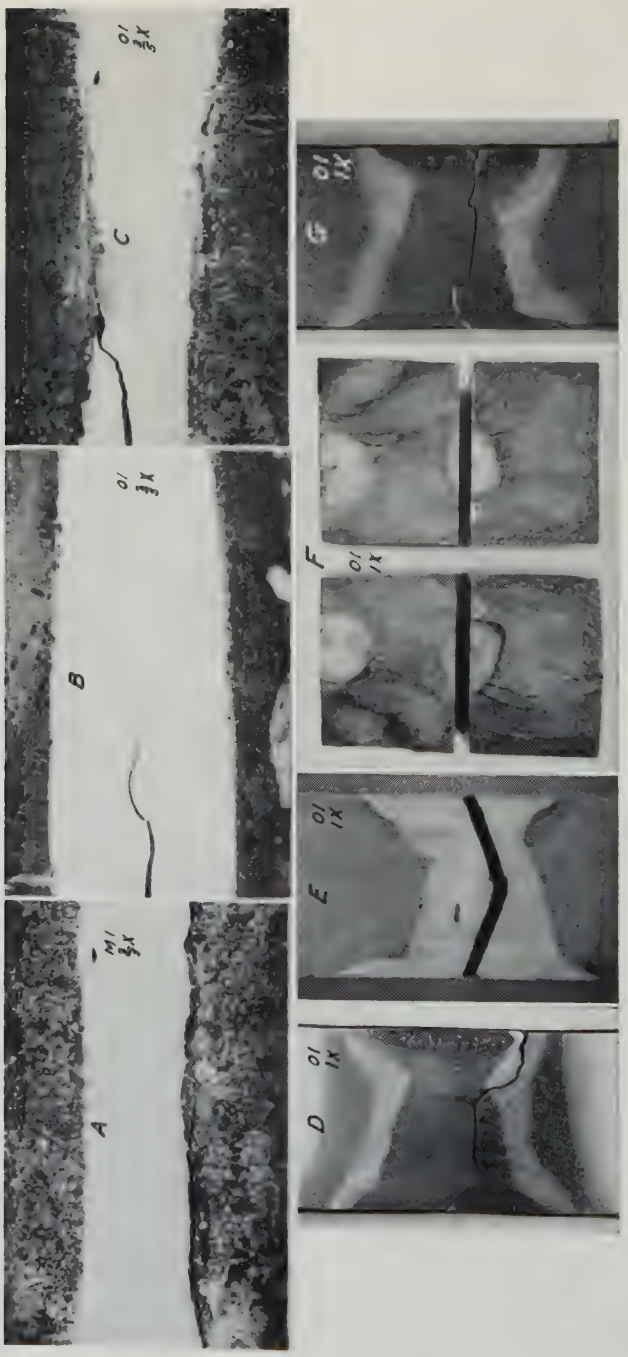
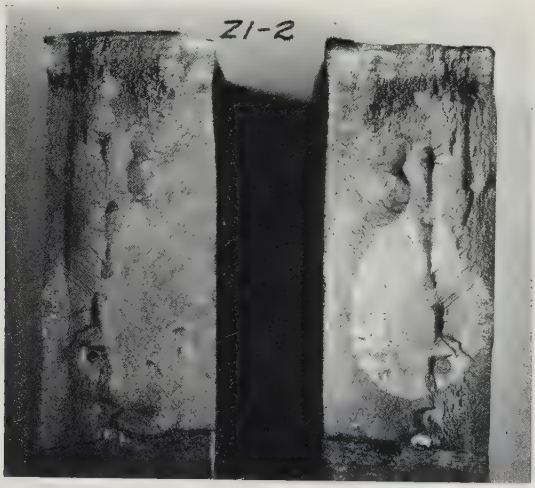


FIG. 11. FATIGUE CRACK THROUGH WELD IN ⅞-IN. CARBON-STEEL PLATE WITH REINFORCEMENT MACHINED OFF



(a)

(b)

FIG. 12. NUCLEI OF BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES THAT FAILED IN THE WELD. REINFORCEMENT GROUND OFF

weld metal, as indicated by the nuclei on the fracture shown in Fig. 11*F*. The path of the fracture, with respect to the various microstructural regions of the transverse section, are shown at *D*, *E*, and *G* of the same figure. The nuclei, from which the fatigue cracks of specimens Z1-2 and Z2-2 started, are shown in Fig. 12. The unusual fracture of specimen PP3, a plate without a weld, is shown in Fig. 13.

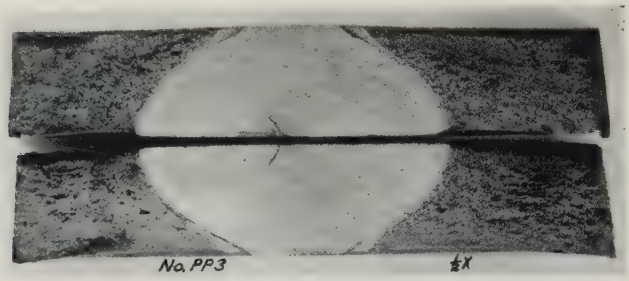


FIG. 13. FRACTURE OF 7/8-IN. CARBON-STEEL PLATE WITHOUT WELD SHOWING SINGLE NUCLEUS NEAR CENTER. SPECIMEN PP3

The fatigue crack originated at a small surface discontinuity at mid-width of the specimen, and spread across the section. When the specimen was subjected to tension, a thickness gage could be run through the specimen at the center before the crack had spread to either edge. Whether a single large stress raiser, as distinguished from either several small ones or a continuous stress raiser along the edge of the reinforcement, caused failure at a small number of cycles is not certain. It is of interest to note, however, that the fatigue-strength ratings of the three specimens, Z1-2, Z2-2, and PP3, each of which had a large fish-eye, were 0.83, 084, and 0.87, respectively.

8. *Summary of Results.*—The results of the individual tests are given in Tables 6 to 12, inclusive, and the average value of the fatigue strength for each group of tests is given in Table 18. A description of the specimen is given in the first column. In general there is a value of $F_{100\,000}$ and one of $F_{2\,000\,000}$ given for each kind of specimen and for each ratio of minimum to maximum stress. Values that are marked with a small circle in Tables 6 to 12 have been omitted from the summary.

The diagrams of Fig. 14a show the effect of the ratio of the minimum to the maximum stress in the stress cycle upon the fatigue strength of specimens in the as-welded condition as determined from the data listed in Table 18. The upper curve is for the fatigue strength corresponding to failure at 100 000 cycles and the lower one for failure at 2 000 000 cycles. Each small circle represents the average of a group of similar tests, the numeral adjacent to a circle indicating the number of tests averaged. Distances to the right or left of the origin represent the minimum stress in the stress cycle; distances above the origin represent maximum stresses. Points to the right and

TABLE 18
FATIGUE STRENGTH OF BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES
Summary of Results

Description of Specimen	Fatigue Strength in 1000's of lb. per sq. in.					
	Tension to an Equal Compression		0 to Tension		Tension to Tension ½ as Great	
	N= 100 000	N= 2 000 000	N= 100 000	N= 2 000 000	N= 100 000	N= 2 000 000
As Welded	22.3	14.4	33.1	22.5	53.3	36.9
Reinforcement On Stress Relieved	21.3	15.1	31.9	23.7		37.6
Reinforcement Machined Off Not Stress Relieved	28.9		48.8	28.4		43.7
Reinforcement Machined Off Stress Relieved	24.5	16.6	49.4	27.8		42.6
Reinforcement Ground Off Not Stress Relieved	26.8		44.5	26.3		
Plain Plate Mill Scale On	27.7	17.1	49.8	31.6		50.0
Plain Plate Mill Scale Machined Off and Surface Polished			59.6			
Butt Weld. Reinforcement and Mill Scale Machined Off and Surface Polished			53.9			

upward represent tension, those to the left represent compression. Thus, the point A indicates that a specimen tested on a cycle in which the stress varied from 22 300 lb. per sq. in. tension to 22 300 lb. per sq. in. compression may be expected to fail at 100 000 cycles. Likewise the point B indicates that the fatigue strength of a specimen tested on a cycle in which the stress varied from zero to tension was 33 100 lb. per sq. in., and the point C indicates that the fatigue strength of a specimen subjected to a cycle in which the stress varied from tension to tension one-half as great was 53 300 lb. per sq. in.

The broken lines of Fig. 14 represent the results of tests, and the full lines represent the empirical equation* $(FL)' = \frac{3\,(FL)}{2 - r}$. In this equation, (FL) is the fatigue strength for a complete reversal, r is the ratio of the minimum to the maximum stress in the stress cycle (r is negative for a complete or partial reversal), and $(FL)'$ is the fatigue strength for any particular value of r. It is of interest to note that if the position of the line representing the empirical equation is determined by the fatigue strength for $r = -1$ (complete reversal of

*See "Materials of Engineering," by Herbert F. Moore, page 55, Fifth Edition. Also Univ. of Ill. Eng. Exp. Sta. Bul. 302, page 77.

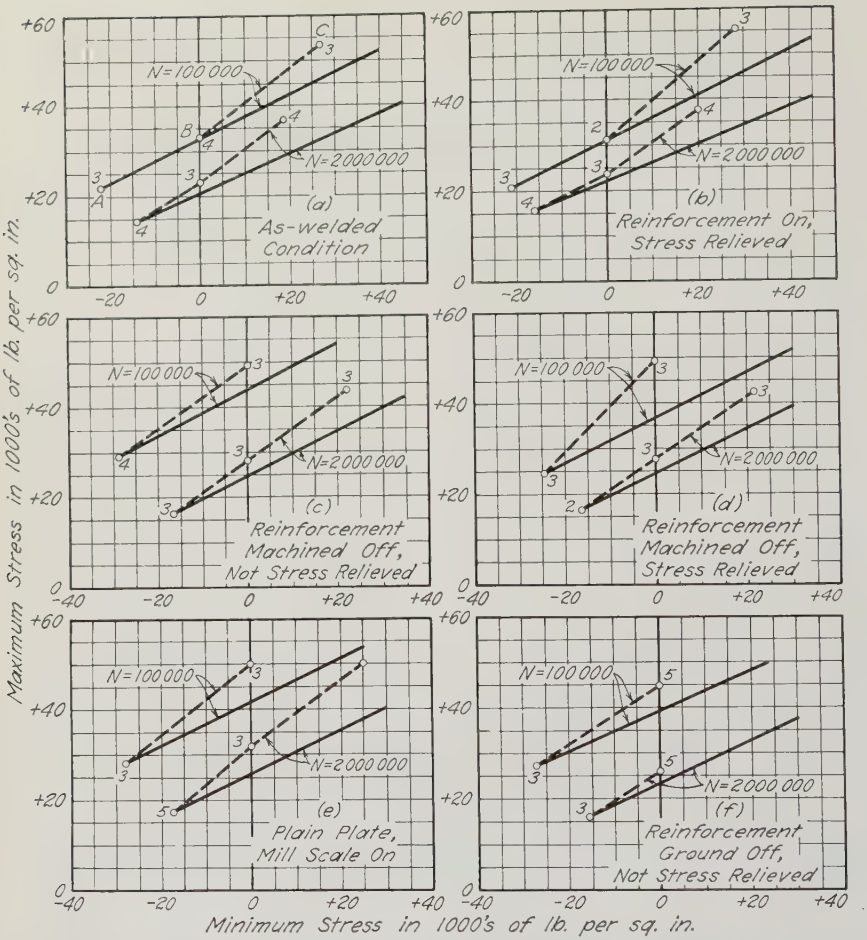


FIG. 14. FATIGUE STRENGTH OF BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES FOR VARIOUS TYPES OF SPECIMENS AND FOR VARIOUS RELATIONS OF MINIMUM TO MAXIMUM STRESS. SUMMARY OF RESULTS

stress), then the line falls below the experimentally-determined points for all other cycles used in this investigation. It is also of interest to note that the agreement between computed and the test values for $r = 0$, was much closer for specimens with the reinforcement on than it was for either specimens with the reinforcement off or for specimens without welds.

For specimens in the as-welded condition, the values of the fatigue strength for a cycle in which the stress varied from tension to an equal

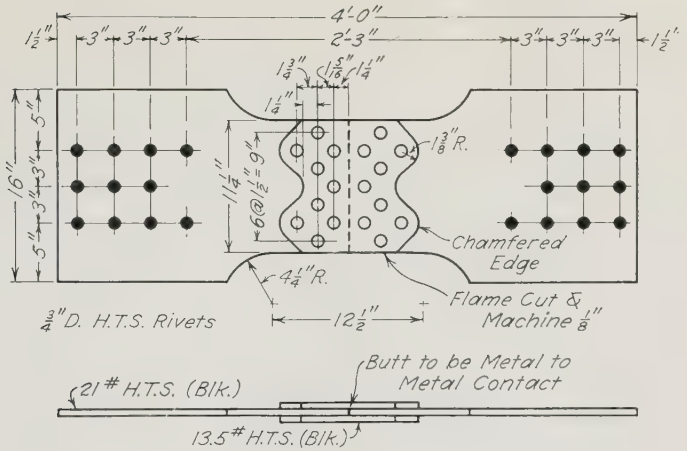


Fig. 15. Details of Riveted Specimens

compression were 22 300 lb. per sq. in. for failure at 100 000 cycles and 14 400 lb. per sq. in. for failure at 2 000 000 cycles; and for a cycle in which the stress varied from zero to tension, the values of the fatigue strength were 33 100 lb. per sq. in. for failure at 100 000 cycles and 22 500 lb. per sq. in. for failure at 2 000 000 cycles.

For specimens in the as-welded condition, except that the reinforcement had been machined flush with the base plate on both sides, the values of the fatigue strength for a cycle in which the stress varied from tension to an equal compression were 28 900 lb. per sq. in. for failure at 100 000 cycles and 16 850 lb. per sq. in. for failure at 2 000 000 cycles. These values are considerably higher than corresponding values reported in the preceding paragraph for similar specimens with the reinforcement on.

A comparison of the fatigue strength of butt welds that were stress-relieved by heat treatment with the fatigue strength of those that were not stress-relieved indicates that stress-relieving did not affect the fatigue strength. This was true for the specimens with the reinforcement off as well as for those with the reinforcement on.

Specimens from which the reinforcement had been machined flush with the base plate on both sides had approximately the same fatigue strength as plates without welds but with the mill scale on.

Specimens from which the reinforcement had been ground flush with the base plate on both sides with a portable grinder had a fatigue strength only slightly lower than that of similar specimens with the reinforcement machined off.

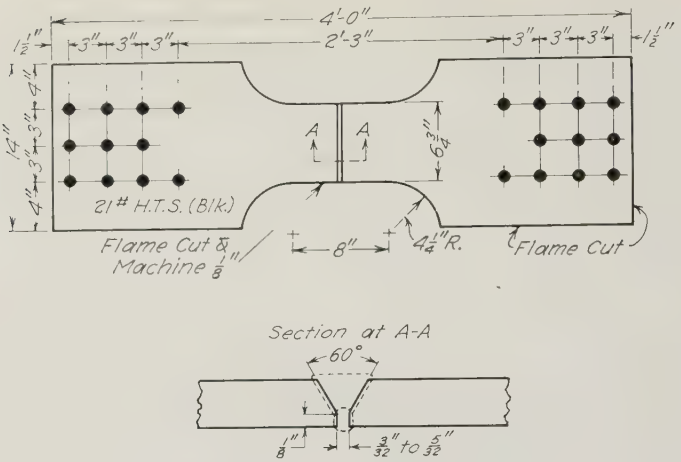


Fig. 16. Details of Welded Specimens

Specimens with the reinforcement and mill scale machined off and the surfaces polished had a fatigue strength somewhat greater than that of specimens with the mill scale on, but considerably lower than that of small round machined and polished specimens.*

For all kinds of specimens, stress-relieved or not stress-relieved, reinforcement off or reinforcement on, the fatigue strength corresponding to failure at 2 000 000 repetitions of a cycle in which the stress varied from tension to tension one-half as great exceeded the yield point of the material, and is therefore not important to the structural designer.

III. Relative Strength of Welded and Riveted Joints in Low-Alloy Steel Plates

9. *Description of Specimens.*—The tests were planned to determine the relative strength of welded and riveted joints connecting plates of a low-alloy steel of structural grade. There were nine each of riveted and welded specimens. Six of the riveted specimens were subjected to fatigue tests and three to static tests. Of the welded specimens, seven were subjected to fatigue tests and two to static tests. The object of the static tests was to determine the strength of the joint, and for the riveted joints, to determine the load-slip relation.

*Univ. of Ill. Eng. Exp. Sta. Bul. 302, Table 40, page 103.

Table 19
Chemical Composition of Cores of Electrodes, Plates, and Deposited Weld Metal

	Carbon	Manganese	Silicon	Chromium	Vanadium	Copper	Phosphorus	Sulphur	Nickel
Electrode....	0.10	0.45	0.02	....	....	0.12	0.014	0.022	0.03
Plate.....	0.16	1.27	0.20	0.02	0.12	0.03	0.022	0.036	....
Weld Metal..	0.06	0.50	0.025	0.01	0.04	0.01	0.021	0.029	....

Table 20
Results of Static Tests of Welded Joints

Specimen No.	Stress, lb. per sq. in. gross area		Reduction of Area per cent	Elongation in 8 in. per cent	Part That Failed
	Yield Point*	Ultimate			
105	60 100	83 000	49.7	23.4	Plate
107	60 200	82 900	....	17.5	Weld

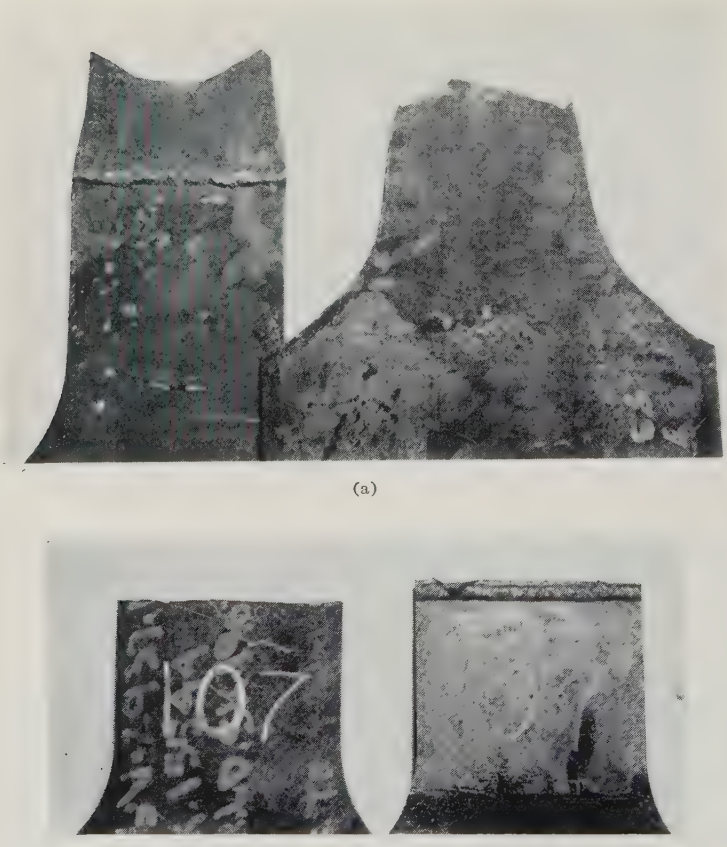
*By drop of beam.

All specimens were made of low-alloy structural* steel plates approximately ½ in. thick and weighing 21 lb. per sq. ft.

The riveted joints, shown in Fig. 15, were of the double-strap butt type with ¾-in. manganese-steel rivets. The driven heads of the rivets were countersunk and chipped; the manufactured heads were of the button type. The ratio of the net to the gross area for these joints was 0.76.†

The welded joints, shown in Fig. 16, were of the single-V butt-weld type welded in a flat position using an electrode conforming to the requirements of the Grade EA of Navy Department Specification 22 W7 (Reid Avery Type HD-7). The welding procedure was as follows: The plates, after being scarfed, were spaced ⅛ in. apart and tack-welded at each end of the groove. The root pass was deposited with a $\frac{5}{32}$-in. electrode using 140 amperes and 27 volts, at a rate of approximately 5 in. per min. Deposition was started at one end of the groove and carried continuously to the other end. The three succeeding layers were deposited with a $\frac{3}{16}$-in. electrode using 180 amperes and 32 volts. A full weave was used, progressing at a rate of three

*This low-allow steel is of the same type as that used in the tests described in Chapter V.
†The net section was computed in accordance with the Specifications for Steel Railway Bridges of the American Railway Engineering Association except that the diameter of the hole to be deducted was taken $\frac{1}{32}$ in. greater than the nominal diameter of the rivet in accordance with Navy practice.



(a)

(b)

FIG. 17. BUTT WELDS IN ALLOY-STEEL PLATES AFTER STATIC FAILURE. SPECIMENS 105 AND 107

to four in. per min., depending upon the width of the groove. All layers were deposited in the same direction as the root pass, and continuously from one end of the groove to the other. Layers were deposited at approximately 15-min. intervals. The root of the groove was chipped out to a depth of ¼ in. from the bottom side and rewelded with a $\frac{5}{32}$-in. electrode, in two layers, using 140 amperes and 27 volts. The slag resulting from the deposit of the successive layers was removed with a light scaling hammer and a wire brush.

The chemical composition of the cores of the electrodes and of the plates is given in Table 19.

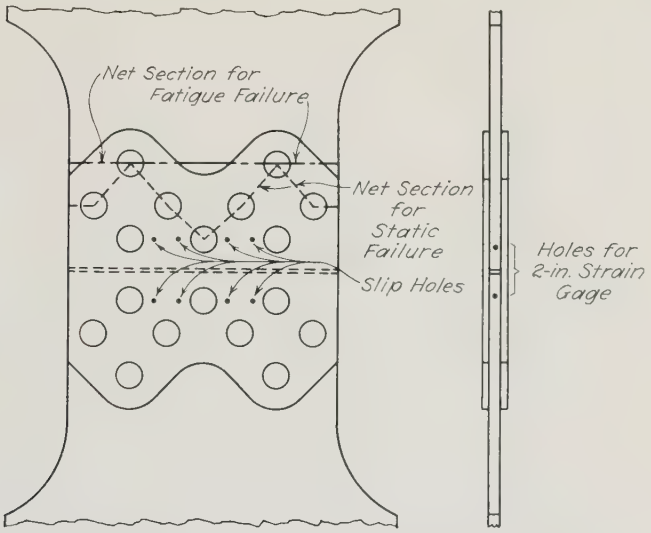


FIG. 18. SKETCH OF RIVETED SPECIMEN SHOWING LOCATION OF SLIP HOLES

10. *Static Tests of Welded Joints.*—The welded specimens 105 and 107 were tested to failure in a static machine. Scaling of the plate outside of the weld was noted for specimen 105 at a stress of 59 000 lb. per sq. in., and there was a definite drop of the beam at a stress of 60 000 lb. per sq. in. For specimen 107, scaling and drop of the beam occurred simultaneously at a stress of 60 200 lb. per sq. in. The results of the tests are given in Table 20.

Figure 17 shows specimens 105 and 107 after failure. Although 107 failed in the weld, it developed as great a strength as 105, which failed outside of the weld.

11. *Static Tests of Riveted Joints.*—Specimens 91, 92, and 93 were tested to failure in a static testing machine. The slip between the main plates and the strap plates was measured with a tapered pin* at various loads at points indicated in Fig. 18. Slip was measured at eight holes for each specimen, two for each plane on which slip occurred for the upper part of the joint and two for each plane for the lower part of the joint. The values of the slip as measured at each pair of holes were averaged and the relation between these average values and the load is shown by the load-slip diagrams of Fig. 19.

The results of the tests are given in Table 21. Attention is called

*Univ. of Ill. Eng. Exp. Sta. Bul. 239, page 10.

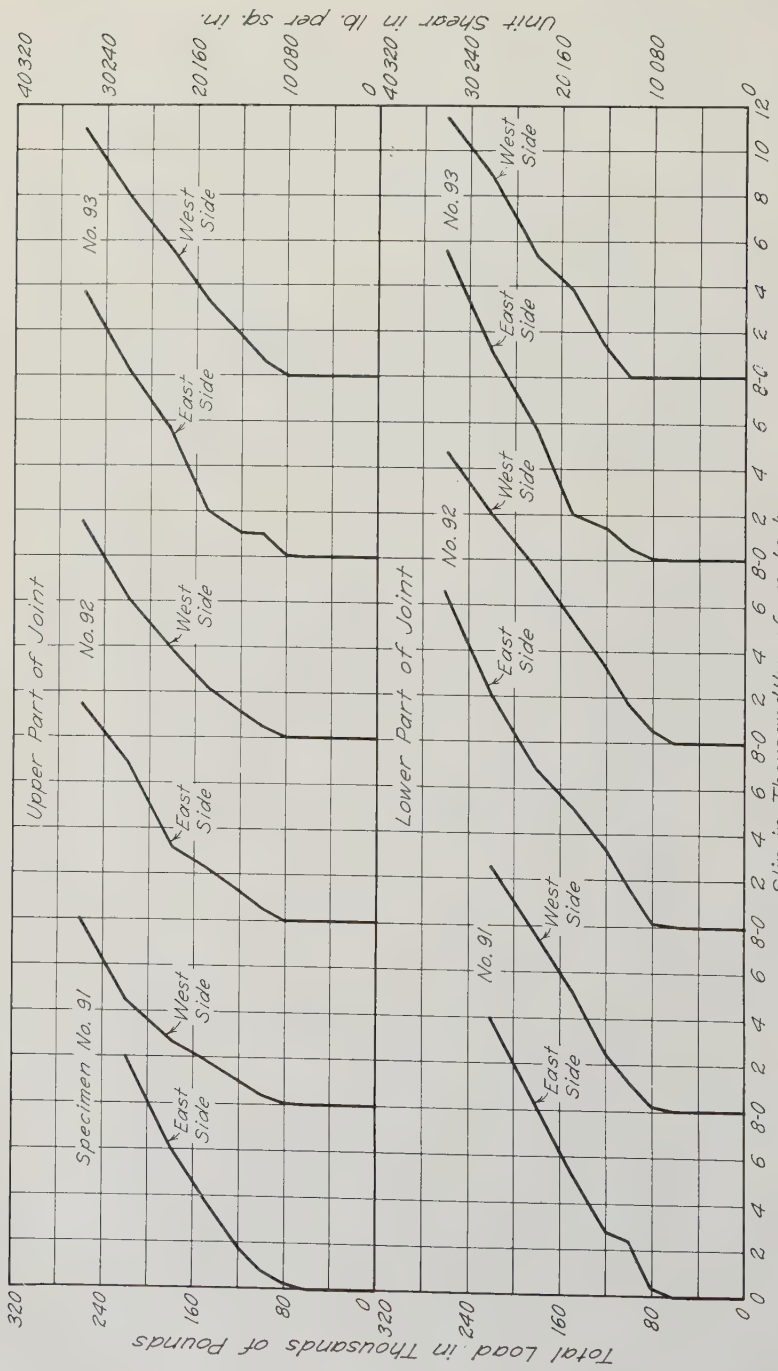


FIG. 19. LOAD-SLIP RELATION FOR SPECIMENS 91, 92, AND 93

TABLE 21
RESULTS OF STATIC TESTS OF RIVETED JOINTS

Specimen No	Stress, lb. per sq. in.				Part That Failed
	Shear on Rivets		Ultimate Tension in Plate		
	at 0.001 in. slip	Maximum	Net Section	Gross Section	
91	12 900	46 700	84 500	64 800	Main Plate
92	13 000	47 200	84 800	64 700	Main Plate
93	13 375	46 500	85 800	64 900	Strap Plate
Av.	13 100	48 800	85 000	64 800	

FIG. 20. RIVETED JOINTS AFTER STATIC FAILURE. SPECIMENS 91 AND 92

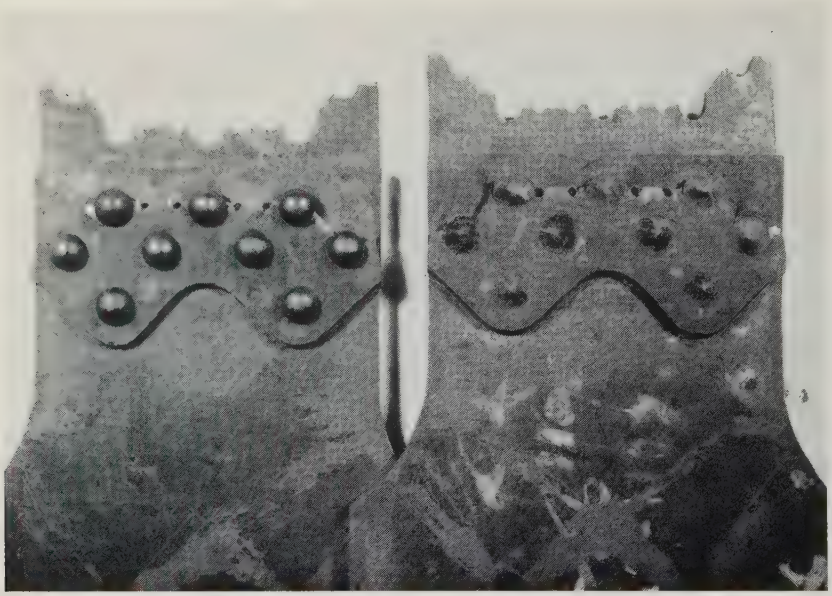


FIG. 21. RIVETED JOINTS AFTER STATIC FAILURE. SPECIMEN 93

to the fact that the unit shear on the rivets that produced an arbitrarily chosen slip of 0.001 in. is very nearly the same for all three specimens. Specimen 93, for which the unit shear on the rivets necessary to produce a slip of 0.001 in. was greatest, developed the highest tensile stress in the plate. Moreover, it was the only riveted joint that failed in the strap plates. Figures 20 and 21 are from photographs of specimens 91, 92, and 93 after failure. For specimens 91 and 92, which failed in the main plate, the line of failure passed through 7 rivets, whereas, for 93, which failed in the strap plates, the line of failure passed through 5 rivets, as shown in the figures. The strength developed by the plates, the average for the three tests, was 85 000 lb. per sq. in. on the net section and 64 800 lb. per sq. in. on the gross section. The latter is comparable with the 83 000 lb. per sq. in. on the gross section developed by the welded specimens.

12. *Fatigue Strength of Welded Joints.*—Seven welded specimens were tested in fatigue. The alignment of the plates was good for all specimens, and the welds contained no defects that could be determined by visual inspection. All specimens were tested in the as-welded condition.

TABLE 22
RESULTS OF FATIGUE TESTS OF WELDED JOINTS: LOW-ALLOY-STEEL PLATES

Specimen No.	Order of Testing	Unit Stress 1000 lb. per sq. in.	Number of Cycles for Failure in 1000s	Fatigue Strength, F 1000 lb. per sq. in.	
				$N = 100\,000$	$N = 2\,000\,000$
106	1	+22 to −22	243.6	25.6	15.4*
108	2	+23 to −23	164.4	25.0	15.0*
104	3	+24 to −24	403.1	30.4	18.3*
102	4	+19 to −19	459.9	24.6*	14.8
103	5	+19 to −19	381.9	23.9	14.3
109	6	+17 to −17	900.9	24.7*	14.9
101	7	+17 to −17	1059.7	25.4*	15.3
				Av. 25.7	15.4

*Values marked with an asterisk (*) were not included in the averages because the ratio n/N for these differed too greatly from unity.

The results of the tests are given in Table 22, the order of testing being given in the second column. Specimens 106, 108, and 104 were tested for failure at 100 000 cycles. Because 106 over-ran, 108 was tested at a somewhat higher stress, but it also over-ran, and 104 was tested at a still higher stress and it over-ran still more. Although the over-run for these tests was greater than is desirable, it is believed that the computed values of the fatigue strength for $N = 100\,000$ are fairly accurate. The test of specimen 102, following the test of 104, was planned for failure at 2 000 000 cycles, but it ran for only a few more cycles than 104, even though the stress was 19 000 lb. per sq.

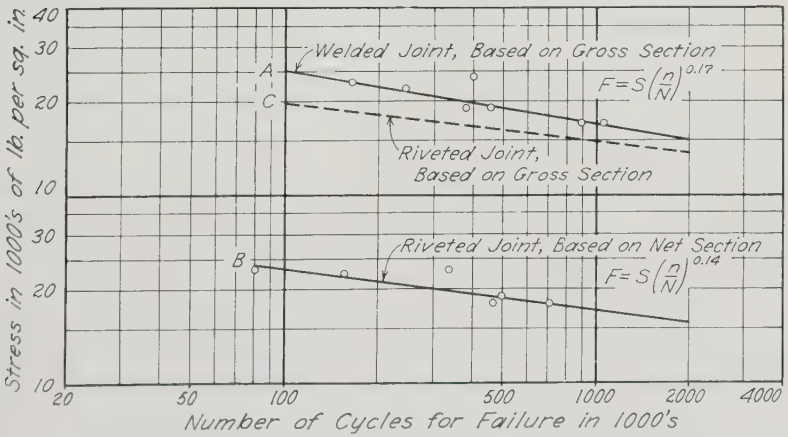


FIG. 22. *S-N* DIAGRAMS FOR RIVETED AND WELDED JOINTS IN LOW-ALLOY-STEEL PLATES. STRESS CYCLE: TENSION TO EQUAL COMPRESSION

FIG. 23. SPECIMEN 104 AFTER FATIGUE FAILURE

in. for the former and 24 000 lb. per sq. in. for the latter. Specimen 103 was tested on the same cycle as 102 and ran very nearly the same number of cycles, a number very much less than the 2 000 000 anticipated. Specimens 109 and 101 were therefore tested at a still lower stress and both ran almost 1 000 000 cycles.

The results of the tests are shown graphically in Fig. 22. There was only one group of tests for the type of specimen used, a number too small to establish a value of K in the equation $F = S(n/N)^K$. Instead, a straight line, A, was located by inspection which, it was believed, represented the results of the tests. The value of K was then determined for the line A and was found to be 0.17. The values of the fatigue strength given in columns 5 and 6 of Table 22 were then computed by the use of the equation $F = S(n/N)^{0.17}$.

Figure 23, from a photograph, shows specimen 104 after failure. The crack extends through the base plate at the lower edge of the weld for almost half of the width of the specimen, then jumps up into the weld metal for a considerable distance near the middle of the specimen; it then jumps up to the junction of the base plate and weld metal at the root of the groove (on the far side of the specimen and not visible in the photograph) for the remaining portion of the width of the specimen. This latter part of the crack was open quite wide on the far side of the plate. Although failure always began at the edge of the deposited metal where the change in section acted as a continuous stress raiser across the specimen, the crack, once started,

meandered through the deposited metal for some specimens. Figure 24 shows the fisheyes on the fractured surface of a number of specimens. The surface of fracture for specimen 108 is made up almost entirely of fisheyes, any one of which would have resulted in failure; nevertheless, the fatigue strength of this specimen was equal to the average. In contrast with this, specimen 106 had two large fisheyes near the center, and 102 and 103 each had a large fisheye at one end. The fisheye for 102, not shown in the figure, was similar to the one for 103. For each of the specimens for which there was a single large fisheye, the crack jumped across the weld bead at the end of the fisheye.

There was no consistent relation apparent between the number and size of the fisheyes and the fatigue strength of the weld for these specimens.

It was thought that there might be some relation between the fatigue strength and the point at which the crack started, the origin of a crack at an edge of a specimen being considered as evidence that the longitudinal force was eccentric. The origin of the crack was noted for each specimen and was as follows: for specimens 101, 104, 106, and 109 failure began at one edge of the specimen and spread toward the other edge; for 102, 103, and 108 it began in the central portion and spread both ways. Of the specimens for which the crack began at one edge, the fatigue strength was above the average for two and below the average for two. Of those for which the crack began near the middle of the specimen, the fatigue strength was below the average for two and above the average for one. Apparently, the fatigue strength of the specimen had no consistent relation to the origin of the crack.

Figure 25 shows the microstructure of the weld at the junction of the base plate and the deposited metal for specimen 103, which is typical of the microstructure of all of the specimens. Each micrograph is numbered and its location is indicated by the corresponding number on the macrograph, also given in each figure. The figure shows the grain size in and adjacent to the last bead that was deposited. The structure of the weld metal at points 1 and 2 is typical of cast metal. The microstructure near the middle of the weld showed the effect of subsequent beads, which heated the first beads that had been deposited, and caused a change in the grain characteristics. Micrograph 6 of Fig. 25 was taken in the heat-affected zone, and 7 was taken in the base plate far enough from the weld so that the grain structure was not affected.

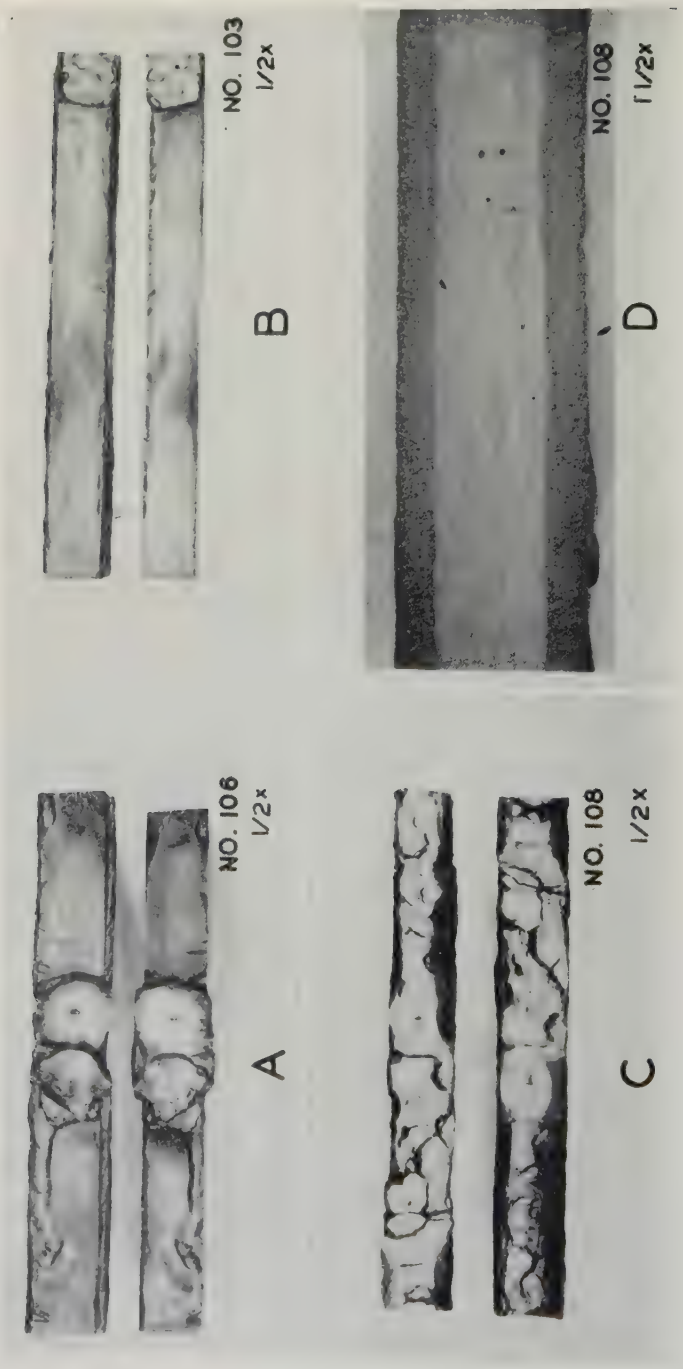


FIG. 24. FISHEYES DEVELOPED IN FATIGUE TESTS OF LOW-ALLOY SPECIMENS THAT BROKE IN THE WELD

Figure 26 shows the hardness gradient* for specimen 103, one diagram being for the upper portion and the other for the central portion of the weld. Although these diagrams are for specimen 103, they are typical of the diagrams for all of the specimens. The deposited metal is not quite as hard as the base plate, and a small area in the heat-affected zone is considerably harder than either the deposited metal or the base plate.

The radiographs of specimens 107 and 108 showed no flaws; the ones for 102, 104, 106, and 109 showed some porosity, but not enough to be satisfactorily reproduced in a cut. The radiographs of 101, 103, and 105 showed a degree of porosity somewhat less than that shown for 102.

Although the radiograph showed no flaws in specimen 108, the macrograph of Fig. 24*D* shows several blow holes. The discovery of blow holes by the method of making sections is partly a matter of chance as they might be cut by some sections and not by others. But, of the specimens tested, 108 is the only one in which blow holes were discovered. The radiograph shows no flaws and the fatigue strength was greater than the average. Considering all the specimens tested, there was no consistent relation between the flaws shown by the radiographs and the fatigue strength of the specimens. The reason small internal flaws had no effect upon the fatigue strength of the specimen may have been due to the fact that failure occurred at the edge of the weld where the change in section acted as a stress raiser extending the full width of the specimen which was more injurious than the internal flaws. There is a possibility, however, that internal flaws might affect the fatigue strength of a specimen not having any large surface stress raisers like a butt weld with the reinforcement planed off.

The results of the tests may be summarized as follows:

The average fatigue strength of the welded joints, tested on a cycle in which the stress was completely reversed, was 25 000 lb. per sq. in. for failure at 100 000 cycles and 15 000 lb. per sq. in. for failure at 2 000 000 cycles. The static strength of similar specimens, given in Table 20, was 83 000 lb. per sq. in.

The value of the fatigue strength apparently was not appreciably affected by any of the following influences: (1) the location of the origin of the crack with respect to the edges of the specimen; (2) the size, number, and distribution of the nuclei; (3) the presence of minor blow holes.

*The hardness was determined with a Vickers type machine and, for the range of hardness studied, the Vickers hardness numbers and the Brinell hardness numbers agree closely.

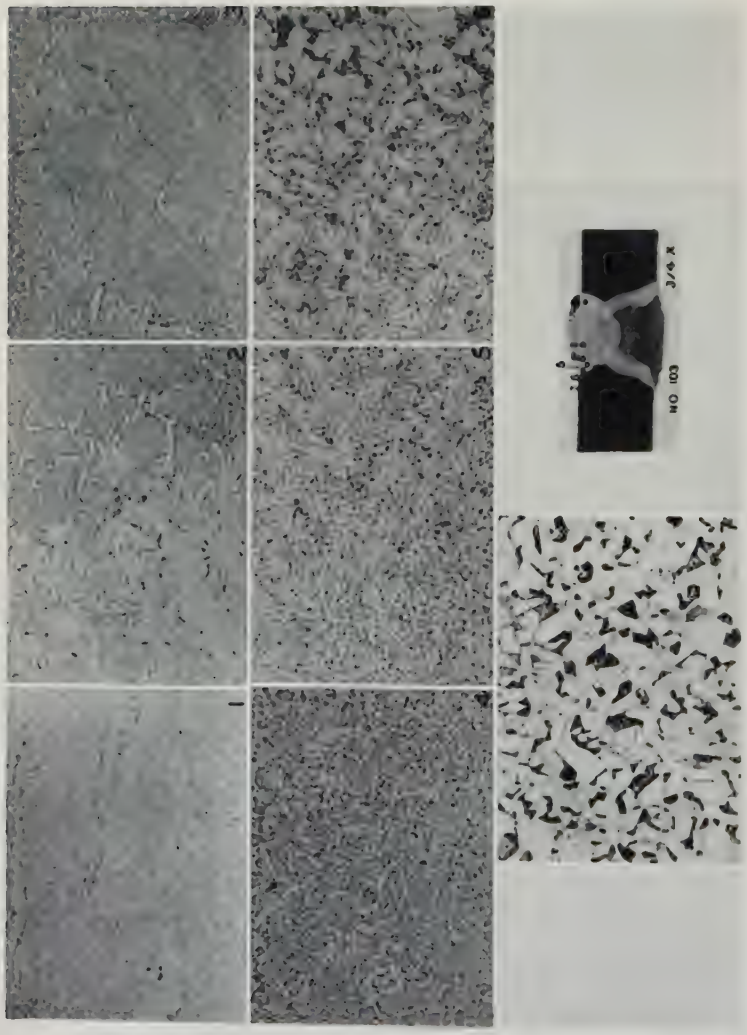


FIG. 25. MICROSTRUCTURE OF WELD IN LOW-ALLOY-STEEL PLATE. SPECIMEN 103

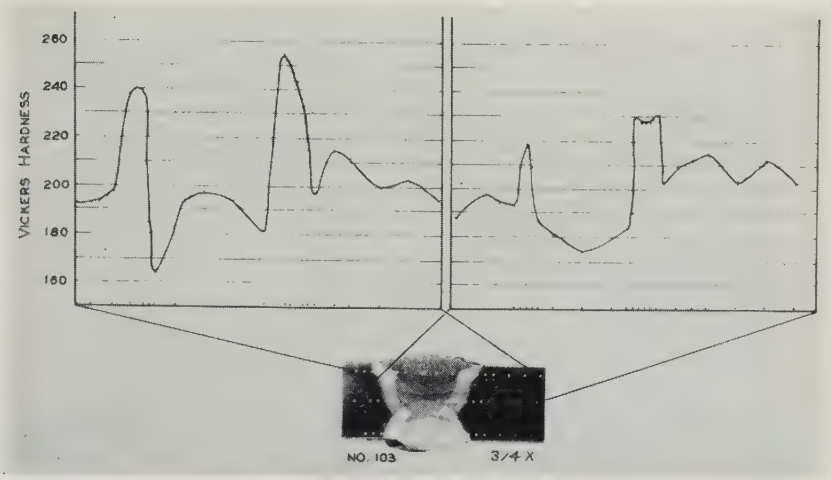


FIG. 26. HARDNESS DIAGRAMS FOR BUTT WELD IN LOW-ALLOY-STEEL PLATE. SPECIMEN 103

All specimens failed at the edge of the reinforcing where the sharp change in section acted as a stress raiser over the full width.

13. *Fatigue Strength of Riveted Joints.*—Six riveted specimens were tested for fatigue failure on a cycle in which the stress varied from tension to an equal compression. The longitudinal edges of the plates of the first specimen tested, number 96, were machined to a point just outside of the strap plates. The remaining portions of the edges were flame-cut. A fatigue crack developed at a notch in the flame-cut edge, where the fillet meets the straight portion of the edge, at about the same time that a crack developed through a rivet hole in the outer row. Both cracks are shown in Fig. 27. The edges of the remaining specimens were machined over their entire length. The net section upon which the unit stress was based is shown in Fig. 18. The fatigue failure occurred on this section for all specimens. Figure 28, from a photograph, shows a typical failure for these joints.

The slip between the plates was measured on the gage lines on the edges of the plates, as shown in Fig. 18. The slip increased as the test continued. The initial slip and the slip at the last reading taken before the specimen failed are given in Table 23.

The results of the tests are given in Table 24 and Fig. 22. As in the case of the welded joints, there was only one group of tests for this type of specimen, a number too small to establish a value of K

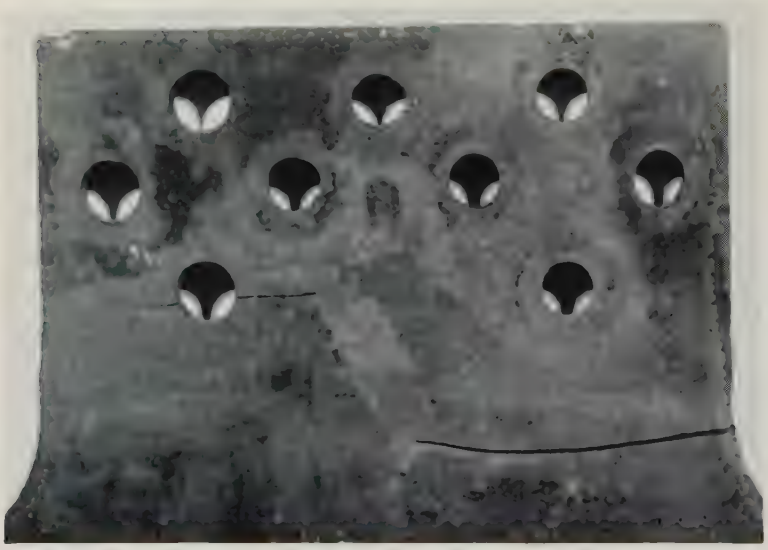


FIG. 27. FATIGUE CRACK THAT ORIGINATED AT EDGE OF PLATE WHERE THE FILLET JOINED THE TANGENT. SPECIMEN 96

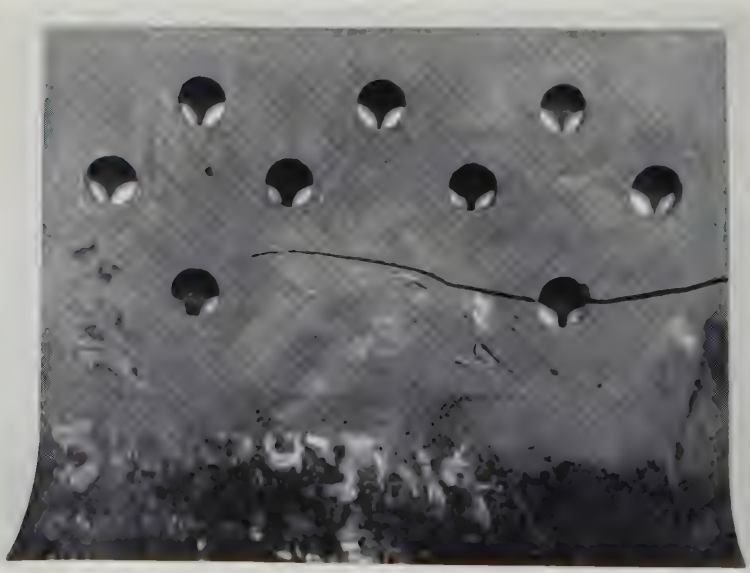


FIG. 28. TYPICAL FATIGUE FAILURE OF PLATE OF RIVETED JOINT. LOW-ALLOY-STEEL PLATE

TABLE 23
RESULTS OF FATIGUE TESTS OF RIVETED JOINTS: SLIP BETWEEN PLATES

Specimen No.	Stress on Net Section 1000 lb. per sq. in.	Slip, inches	
		Initial Reading	Final Reading
96	+22.4 to −22.4	0.0090	0.0104
97	+23.0 to −23.0	0.0119	0.0198
94	+23.0 to −23.0	0.0091	0.0130
95	+19.0 to −19.0	0.0086	0.0175
99	+18.0 to −18.0	0.0102	0.0250
100	+18.0 to −18.0	0.0075	0.0390

for the type. Instead, a straight line, B, was located by inspection which, it was believed, represented the results of the tests. The value of K was then determined for the line B and was found to be 0.14. The values of the fatigue strength given in columns 5 and 6 of Table 24 were then computed by the use of the equation $F = S(n/N)^{0.14}$.

Line B is based upon the net transverse section of the plate through the outer row of rivets. Because line A, for the welded joints, is based upon the gross area, the values of the fatigue strength of the riveted joints, based on the gross section, were also computed. These values

TABLE 24
RESULTS OF FATIGUE TESTS OF RIVETED JOINTS: LOW-ALLOY-STEEL PLATES

Specimen No.	Order of Testing	Unit Stress on Net Section 1000 lb. per sq. in.	Number of Cycles for Failure in 1000s	Fatigue Strength, 1000 lb. per sq. in. Based on			
				Net Section		Gross Section	
				N = 100 000	N = 2 000 000	N = 100 000	N = 2 000 000
96	1	+22.4 to −22.4	155.4	23.8	15.7*	20.1	13.3*
97	2	+23.0 to −23.0	337.9	27.3	17.9*	23.1	15.1*
94	3	+23.0 to −23.0	80.3	22.3	14.7*	18.7	12.4*
95	4	+19.0 to −19.0	500.4	23.8*	15.7	20.1*	13.3
99	5	+18.0 to −18.0	466.0	22.3*	14.7	18.7*	12.4
100	6	+18.0 to −18.0	707.8	23.7*	15.6	20.0*	13.2
				Av. 23.9	15.7	20.1	13.3

*Values marked with an asterisk (*) were not included in the averages because the ratio n/N for these differed too greatly from unity.

are given in Table 24 and are represented by the dotted line C of Fig. 22. The relative positions of lines A and C indicate that, on the basis of the gross section, the fatigue strength of joints in low-alloy steel plates is definitely higher for welded than for riveted joints.

14. *Summary of Results.*—The results obtained from the tests described in the preceding sections apparently justify the following conclusions.

(1) The low-alloy structural steel plates had a static strength based on the gross area of 83 000 lb. per sq. in. when fabricated by welding and of 64 800 lb. per sq. in. when fabricated by riveting. The strength of the latter based on the net section was 85 000 lb. per sq. in.

(2) The low-alloy structural steel plates had a fatigue strength based on the gross area and corresponding to failure at 100 000 cycles of 25 000 lb. per sq. in. when fabricated by welding and of 19 800 lb. per sq. in. when fabricated by riveting. For failure at 2 000 000 cycles, the corresponding values were 15 000 lb. per sq. in. and 13 800 lb. per sq. in. for welded and riveted joints, respectively. These values of the fatigue strength are for a cycle in which the stress varied from tension to an equal compression.

(3) The fatigue cracks in the riveted specimens passed through the holes in the outer row. Those in the welded specimens always began at the edge of the deposited metal where the abrupt change in section acted as a stress raiser that extended the full width of the specimen.

IV. Effect of Periods of Rest Upon Fatigue Strength of Butt Welds

15. *Description of Tests.*—Fatigue tests are usually run continuously, whereas the structural members of a bridge floor, the members most likely to be affected by fatigue, are subjected to a number of cycles in rapid succession and then rest for a considerable period. The question has often been asked whether or not the fatigue strength obtained from continuous tests is applicable to structures which have alternate periods of rest and of frequently repeated loads. In order to answer this question a series of tests was planned to determine the effect of rest periods upon the fatigue strength. For this purpose two machines were constructed which could be run either continuously at 180 r.p.m. or adjusted so that they could be run continuously for 100

TABLE 25
PHYSICAL PROPERTIES OF PLATES AND CHEMICAL COMPOSITION OF PLATES AND WELD METAL USED IN REST TESTS

		Stresses, lb. per sq. in.		Reduction of Area per cent
		Yield Point	Ultimate Strength	
Plates	Range	30 500 to 33 000	56 000 to 59 000	51.0 to 58.0
	Average	31 900	57 700	55.4

		Chemical Composition					
		Carbon	Manganese	Silicon	Copper	Phosphorus	Sulphur
Plates	Range	0.22 to 0.28	0.43 to 0.46	0.01 to 0.02	0.15 to 0.18	0.012 to 0.019	0.030 to 0.037
	Average	0.27	0.45	0.01	0.166	0.015	0.034
Weld Metal	Range	0.09 to 0.11	0.30 to 0.33	0.07 to 0.11	0.06 to 0.08	0.017 to 0.021	0.028 to 0.036
	Average	0.10	0.31	0.08	0.07	0.020	0.034

cycles and then stopped for a predetermined period. The period of rest was 5 minutes for one machine and 30 minutes for the other. The machines, which had a capacity of 50 000 lb., were automatic and ran night and day without an attendant.

The details of the specimens used in the rest tests are shown in Fig. 2. All specimens were cut from one parent plate and the same electrode and the same welding procedure was used for all specimens. Tension control specimens and chemical samples were taken at various points over the plate to determine its uniformity. The physical properties and the chemical composition are given in Table 25.

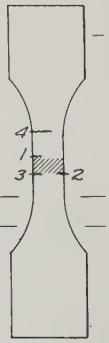
A survey of the microstructure and hardness of the weld joint indicated that the fatigue strength would not be materially affected by the metallurgical structure of the weld. The maximum hardness in the heat-affected zone of the plate varied from 134 to 166 Vickers, values that are acceptable. The plate metal had an average hardness of 120, and the weld metal had an average hardness of 125. The structure in the heat-affected zone of the plate was a very fine pearlite which had good properties of strength and ductility.

The method of making a test was as follows: Nine identical specimens were selected for a series to be tested at a given cycle, the

TABLE 26

EFFECT OF PERIODS OF REST UPON FATIGUE STRENGTH OF BUTT WELDS IN ½-IN. CARBON-STEEL PLATES

Spec. No.	Rest Period	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, n, in 1000's	Strength in 1000's of lb. per sq. in.			Location of Fatigue Crack
				Static	Fatigue, F,*		
					N=100 000	N=2 000 000	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Cycle: Tension to an Equal Compression							
C1	No Rest	+20.0 to -20.0	85.8	57.3	19.7	14.6 •	1
C2		+20.0 to -20.0	119.7	57.3	20.4	15.1 •	2
C3		+20.0 to -20.0	108.2	57.3	20.2	14.9 •	3
					Av. 20.1		
E1		+16.0 to -16.0	1248.2	57.3	20.7 •	15.3	4
E2		+16.0 to -16.0	990.0	57.3	20.1 •	14.9	1
E3		+16.0 to -16.0	3994.2	57.3	21.6 •	16.0+	No Failure
						Av. 15.4	
A1	5 Minutes	+20.0 to -20.0	213.2	57.3	21.6	16.0 •	1
A2		+20.0 to -20.0	146.9	57.3	20.8	15.4 •	3
A3		+20.0 to -20.0	61.9	57.3	19.1	14.1 •	1
					Av. 20.5		
D1		+16.0 to -16.0	233.9	57.3	17.4 •	12.9	1
D2		+16.0 to -16.0	562.2	57.3	19.0 •	14.1	1
D3		+16.0 to -16.0	705.9	57.3	19.5 •	14.4	1
I1		+16.0 to -16.0	611.4	57.3	19.2 •	14.2	1
I2		+16.0 to -16.0	880.9	57.3	19.9 •	14.7	1
I3		+16.0 to -16.0	404.4	57.3	18.4 •	13.6	1
						Av. 14.0	
B1	30 Minutes	+20.0 to -20.0	120.6	57.3	20.4	15.1 •	1
B2		+20.0 to -20.0	132.8	57.3	20.6	15.3 •	1
B3		+20.0 to -20.0	40.5	57.3	18.3	13.5 •	1
H1		+20.0 to -20.0	77.1	57.3	19.5	14.4 •	1
H2		+20.0 to -20.0	257.6	57.3	22.0	16.3 •	4
H3		+20.0 to -20.0	61.0	57.3	19.0	14.1 •	2
					Av. 20.0		
Cycle: 0 to Tension							
M1	No Rest	0 to +35.0	172.1	57.3	37.0	27.4 •	1
M2		0 to +35.0	191.4	57.3	37.4	27.7 •	1
M3		0 to +35.0	250.5	57.3	38.4	28.4 •	1
					Av. 37.6		
G1		0 to +30.0	453.0	57.3	34.9 •	25.8	1
G2		0 to +30.0	1791.2	57.3	40.0 •	29.7	1
G3		0 to +30.0	485.8	57.3	35.1 •	26.0	1
J1		0 to +27.0	540.3	57.3	32.0 •	23.7	1
J2		0 to +27.0	1455.9	57.3	35.3 •	26.2	1
J3		0 to +27.0	4547.0	57.3	36.5 •	27.0+	1
						Av. 26.4	
F1	5 Minutes	0 to +30.0	314.1	57.3	33.6	24.9 •	1
F2		0 to +30.0	473.9	57.3	35.1	26.0 •	1
F3		0 to +30.0	365.7	57.3	34.2	25.3 •	1
					Av. 34.3		
L1		0 to +27.0	337.6	57.3	30.5 •	22.4	1
L2		0 to +27.0	1066.9	57.3	34.2 •	25.4	1
L3		0 to +27.0	490.7	57.3	31.7 •	23.5	1
						Av. 23.8	
N1	30 min.	0 to +35.0	120.0	57.3	35.6	26.4 •	1
N2		0 to +35.0	81.2	57.3	34.3	25.4 •	1
O1		0 to +35.0	93.9	57.3	34.8	25.8 •	1
					Av. 34.9		



*$F = S\left(\frac{n}{N}\right)^{0.10}$

•Values marked • not included in averages.

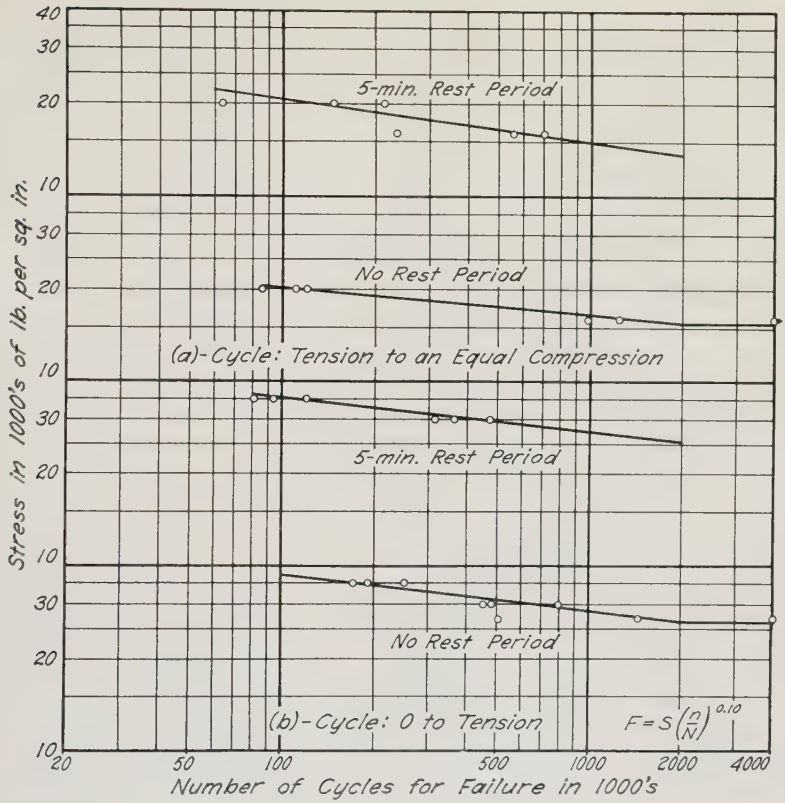


FIG. 29. *S-N* DIAGRAMS FOR BUTT WELDS IN ½-IN. CARBON-STEEL PLATES

maximum stress in the cycle and the ratio of the minimum to the maximum stress to be the same for all. Three were tested continuously, three were tested with 5-min. rest periods following each 100 cycles and three were tested with 30-min. rest periods following each 100 cycles. Some series were planned for failure at 100 000 cycles, others for failure at 2 000 000 cycles. The latter, however, did not include the tests with 30-minute rest periods because of the time that would be necessary for such a test. All specimens were tested with the reinforcement on.

The results of the individual tests are given in Table 26, and the *S-N* diagrams for all of the tests except those with a 30-minute rest period are given in Fig. 29. There were not enough data to determine the *S-N* diagrams from tests with a 30-min. rest period, but the

TABLE 27

EFFECT OF PERIODS OF REST UPON FATIGUE STRENGTH OF BUTT WELDS IN ½-IN. CARBON-STEEL PLATES

Summary of Results

	Stress 1000 lb. per sq. in.	Fatigue Strength,* 1000 lb. per sq. in.				
		N = 100 000†			N = 2 000 000	
		No Rest	5-minute Rest	30-minute Rest	No Rest	5-minute Rest
Full Reversal	+20.0 to −20.0	20.1	20.5	19.8‡ 20.2		
	+16.0 to −16.0				15.4	14.2‡ 13.8
Zero to Tension	0 to +30.0		34.3		27.2	
	0 to +27.0				25.6	23.8
	0 to +35.0	37.6		34.9		

*Each value represents the average of three tests.
†N represents the number of cycles for failure.
‡Two groups of three tests each at this rest period with average fatigue strengths as shown.

equation of the other S-N diagrams was $F = S(n/N)^{0.10}$* and, since the specimens were identical, it has been assumed that the same equation applies for tests with a 30-min. rest period. The values of F given in columns 6 and 7 of Table 26 have been computed from the data in columns 3 and 4 by the use of that equation. The average values given in Table 26 are repeated in Table 27, which is a summary of the results of all of the tests to determine the effect of periods of rest upon the fatigue strength of butt welds in ½-in. carbon-steel plates.

The difference between the fatigue strengths given by rest tests and by continuous tests had an average value of 5 per cent and a maximum value for any one series of 10 per cent, the values obtained from the rest tests being slightly less than those obtained from the continuous tests. It would seem, therefore, that rest periods did not have a significant effect upon the fatigue strength of the welded joints.

Unpublished results obtained by Moore and Putnam at the University of Illinois showed a similar lack of significant effect of rest upon the fatigue strength of small polished specimens.

*The fact that K was found to be 0.10 for butt welds in ½-in. plates and 0.13 for butt welds in ⅞-in. plates may have been due to the difference in the thickness of the plates.

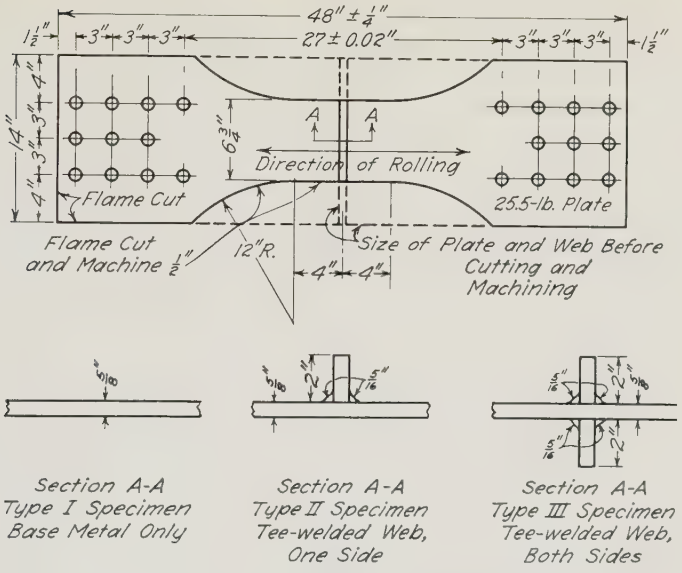


FIG. 30. DETAILS OF SPECIMENS

V. TESTS TO DETERMINE EFFECT OF TRANSVERSE FILLET WELDS UPON FATIGUE STRENGTH OF STEEL PLATES

16. *Description of Specimens and Tests.*—The object of the tests was to determine the effect of transverse fillet welds upon the fatigue strength of steel plates. Three types of specimens were used, the details of which are shown in Fig. 30. Type I was a continuous plate without welds or joints and with mill scale on both sides; type II had a narrow transverse plate attached to one side of the main plate with two transverse fillet welds; type III had transverse plates attached to both sides of the main plate. The main plate was continuous for all three types of specimens.

Specimens of each of the three types were made of two grades of steel, a medium-grade carbon steel and a low-alloy steel.* Each of the six groups contained six identical specimens that were tested in fatigue on a cycle in which the stress varied from tension to an equal compression.

Six coupon specimens of each material were tested for the purpose

*This low-alloy steel is of the same type as that used in the tests described in Chapter III.

Table 28
Physical Properties of Base Plates

Specimen No.	Yield Point lb. per sq. in.	Ultimate Strength lb. per sq. in.	Elongation in 8 in. per cent	Reduction of Area per cent
		Carbon-Steel Plates		
N1	34 250	59 800	31.0	52.8
N2	34 000	58 700	31.0	56.7
N3	34 000	58 200	31.0	55.1
N4	35 000	58 100	31.8	57.8
N5	35 200	58 400	28.1	51.6
N6	34 600	59 100	31.4	56.4
Av.	34 500	58 700	30.7	55.1
		Low-Alloy Plates		
M	58 500	79 000	21.6	61.3
N	58 700	79 700	20.7	62.5
O	59 500	79 250	21.0	62.0
P	59 000	79 200	21.0	59.8
Q	59 400	78 700	21.4	62.2
R	59 650	77 800	17.5	61.5
Av.	59 125	78 940	20.5	61.5

of determining the yield point, ultimate strength, per cent elongation in 8 inches, and per cent reduction of area. The results of the tests are given in Table 28. The average values of the physical properties were as follows:

The carbon-steel plates had a yield point of 34 500 lb. per sq. in., an ultimate strength of 58 700 lb. per sq. in., an elongation in 8 inches of 30.7 per cent, and a reduction of area of 55.1 per cent.

The alloy steel had a yield point of 59 125 lb. per sq. in., an ultimate strength of 78 940 lb. per sq. in., an elongation in 8 inches of 20.5 per cent, and a reduction of area of 61.5 per cent.

Stress–strain data were taken for two specimens of each material and the resulting stress–strain diagrams are given in Fig. 31.

Drillings from the base plate and from the deposited metal were analyzed and the chemical composition is given in Table 29.

The welding procedure was as follows: In fabricating the specimens with a single member normal to the base plate, the plate was placed in the horizontal position, the normal member tack-welded to the plate, and the assembly completed with a single-pass horizontal fillet weld on each side of the normal member. For the specimens that had normal members on both sides of the base plate, one side was fabricated as described, the specimen was then turned over and the process repeated. Data relating to the welding are given in Table 30.

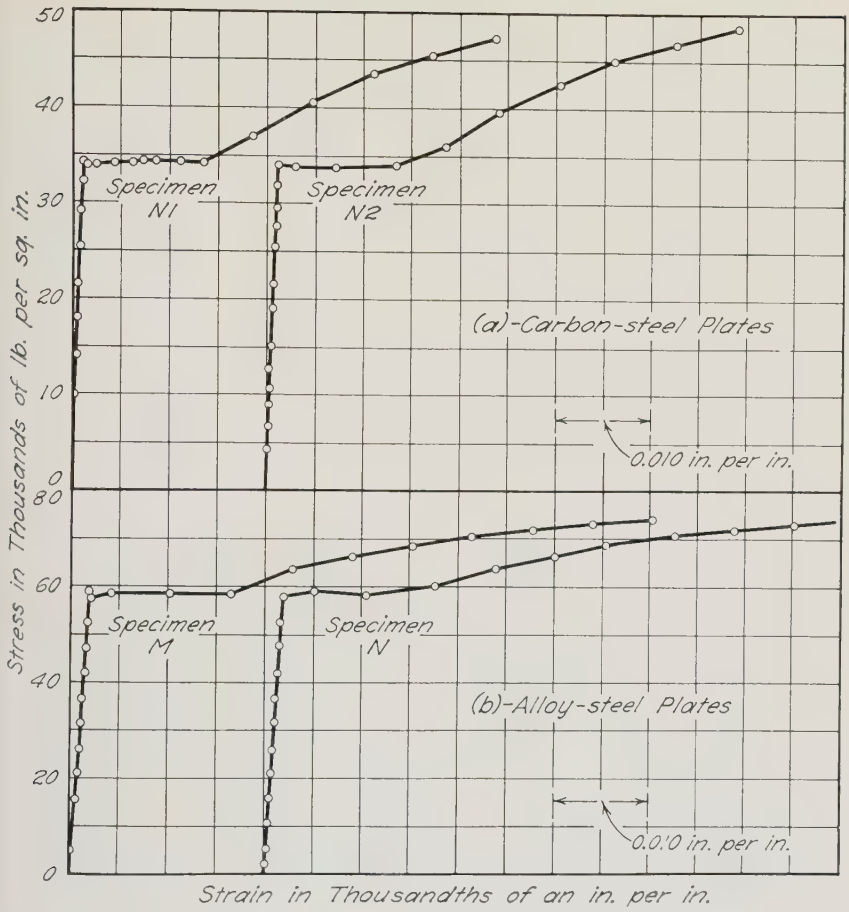


FIG. 31. STRESS–STRAIN DIAGRAMS FOR CARBON-STEEL PLATES AND LOW-ALLOY-STEEL PLATES

17. *Results of Tests.*—The details of the tests are reported in Tables 31 and 32, and the *S-N* diagrams are given in Fig. 32. The specimens were originally made with a fillet radius of 4¼ in., but the first three specimens tested, 7, 8, and 9, Table 31, all broke in the fillet. The remaining specimens were then machined to a 12-in. radius. Specimens 7, 8, and 9 probably broke at a smaller number of cycles than they otherwise would because of the small fillet radius. For that reason these tests were not considered in drawing the lower *S-N* diagram of Fig. 32. For all other *S-N* diagrams, the points representing individual tests were located and a straight line was drawn

Table 29
Chemical Composition of Plates and Weld Metal

Element	Carbon Steel		Alloy Steel	
	Plate	Weld Metal	Plate	Weld Metal
Carbon	0.233	0.09	0.165	0.08
Manganese	0.515	0.500	1.22	0.52
Phosphorus	0.0147	0.015	0.022	0.0165
Sulphur	0.041	0.026	0.066	0.025
Silicon	0.016	0.215	0.20	0.23
Copper	0.22	0.06	0.02	0.015
Chromium	0.075	0.012	0.03	0.01
Vanadium	0.01	0.01	0.10	0.01

which, it was believed, represented the average results. The value of K was then determined which made the equation $F = S\,(n/N)^K$ fit the line. The value of K for each line is given on the diagrams. The exponent K had a value of 0.10 for the type II specimens of alloy steel and that value was therefore used in drawing the S-N diagram for the type II specimen of carbon steel, the lower diagram of Fig. 32. The position of the line was determined from the three points to the right; the three points to the left, which were believed to be too low, being ignored.

The values of F for the individual tests, computed by the use of the empirical equation $F = S\,(n/N)^K$, are given in columns 5 and 6

Table 30
Data Relating to Welding

Base Material	Carbon Steel	Alloy
Type of Electrode	EA	EA
Size of Electrode	3/16 in.	3/16 in.
Electrode Manufacturer	Reid-Avery Co.	Reid-Avery Co.
Number of Passes per Weld	1	1
Open Circuit Voltage	63	63
Arc Volts	26	26
Arc Amperes	170	170
Position	Flat	Flat

TABLE 31
FATIGUE STRENGTH OF PLATES WITH TRANSVERSE FILLET WELDS; CARBON-STEEL PLATES

Specimen No.	Specimen Type	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, n, in 1000's	Fatigue Strength, F,* in 1000's of lb. per sq. in. N=100 000	Fatigue Strength, F,* in 1000's of lb. per sq. in. N=2000 000	Location of Fatigue Crack
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1		+28.0 to -28.0	72.9	27.6	23.7 •	1 (Central Part)
2		+28.0 to -28.0	46.3	27.0	23.2 •	1 (Central Part)
3		+26.0 to -26.0	308.5	27.5	23.7 •	2
4		+24.0 to -24.0	195.8	24.8	21.4 •	2
5		+24.0 to -24.0	100.4	24.0	20.7 •	1 (Central Part)
6		+24.0 to -24.0	93.9	23.9	20.6 •	2
	K=0.05			Av. 25.8		
7		+21.0 to -21.0	147.8	21.8 •	16.1 •	2
8		+21.0 to -21.0	302.7	23.5 •	17.4 •	3
9		+21.0 to -21.0	242.0	22.9 •	17.0 •	3
10		+21.0 to -21.0	563.9	25.0 •	18.5	1
11		+20.0 to -20.0	1478.6	26.2 •	19.4	1
12		+20.0 to -20.0	1186.5	25.6 •	19.0	1
	K=0.10				Av. 18.9	
13		+21.0 to -21.0	132.3	22.1	12.9 •	1
14		+21.0 to -21.0	151.7	22.6	13.2 •	1
15		+21.0 to -21.0	215.6	24.1	14.1 •	1
16		+17.5 to -17.5	434.4	22.8 •	13.3	1
17		+15.0 to -15.0	754.2	21.6 •	12.3	1
18		+14.0 to -14.0	1687.7	23.3 •	13.6	1
	K=0.18			Av. 22.9	Av. 13.1	

*$F = S\left(\frac{n}{N}\right)^K$

• Values marked • not included in averages.

of Tables 31 and 32, the value of K used for each group of tests being as given on the corresponding S-N diagram.

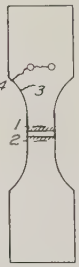
The values of the fatigue strength for the various groups of specimens given in Tables 31 and 32 are summarized in Table 33.

18. *Discussion of Results.*—The fatigue strength of the type I and type II specimens was significantly greater for the alloy steel than it was for the carbon steel. For the type III specimens, the fatigue strength for failure at 100 000 cycles was approximately the same for the two kinds of steel, but, for failure at the larger number of cycles, the fatigue strength was somewhat less for the alloy than it was for the carbon steel.

The specimens have been examined in order to learn whether or not there was any correlation between characteristics of the specimens and their fatigue strength. This examination included a determination of the contour of the welds and a hardness survey and study of the microstructure in and near the heat-affected zone.

TABLE 32
FATIGUE STRENGTH OF PLATES WITH TRANSVERSE FILLET WELDS; ALLOY-STEEL PLATES

Specimen No.	Specimen Type	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, n, in 1000's	Fatigue Strength, F,* in 1000's of lb. per sq. in. N=100 000	Fatigue Strength, F,* in 1000's of lb. per sq. in. N=2 000 000	Location of Fatigue Crack
(1)	(2)	(3)	(4)	(5)	(6)	(7)
37		+30.0 to −30.0	553.0	35.6 •	26.4	3
38		+30.0 to −30.0	409.9	34.6 •	25.6	3
39		+30.0 to −30.0	763.7	36.8 •	27.2	4
40		+34.0 to −34.0	153.3	35.5	26.3 •	3
41		+34.0 to −34.0	201.6	36.5	27.0 •	3
42		+34.0 to −34.0	96.3	33.9	25.1 •	3
	K=0.10			Av. 35.3	Av. 26.4	
43		+25.0 to −25.0	831.0	30.9 •	22.9	2
44		+25.0 to −25.0	1017.5	31.5 •	23.4	3
45		+25.0 to −25.0	2667.9	34.7 •	25.0	No Failure
46		+28.0 to −28.0	500.0	32.9 •	24.4	1
47		+29.0 to −29.0	299.7	32.4	24.0 •	1
48		+29.0 to −29.0	193.9	31.0	22.9 •	1
	K=0.10			Av. 31.7	Av. 23.9	
49		+21.0 to −21.0	130.4	22.5	10.3 •	1
50		+21.0 to −21.0	89.0	20.4	9.4 •	1
51		+21.0 to −21.0	157.8	23.7	10.9 •	1
52		+14.0 to −14.0	873.7	24.6 •	11.3	1
53		+14.0 to −14.0	475.9	21.0 •	9.6	1
54		+13.0 to −13.0	590.1	20.6 •	9.5	1
	K=0.26			Av. 22.2	Av. 10.1	



$*F = S\left(\frac{n}{N}\right)^K$

• Values marked • not included in averages.

The height of the weld and the thickness of the throat were measured with the weld gage* shown in Fig. 33. These measurements indicated that, in general, the throat thickness was slightly less for the carbon-steel specimens than it was for the specimens made of the alloy steel. The welds for each of the two plate materials had distinguishing characteristics in spite of the fact that the same electrode and the same position and procedure in welding were used for both. In general, the welds on the carbon-steel specimens not only had a smaller throat than those on the alloy specimens, but the angle between the fillet surface and the face of the base plate was also smaller. Figures 34 and 35 show typical fillets for the two kinds of plate material. It should be noted that the fatigue crack followed the junction of the weld and main plate for all specimens.

Because the bead played such an important part in the fatigue failure, all specimens containing welds were given a bead rating which

*This gage was developed by the Bureau of Construction and Repair, U. S. Navy.

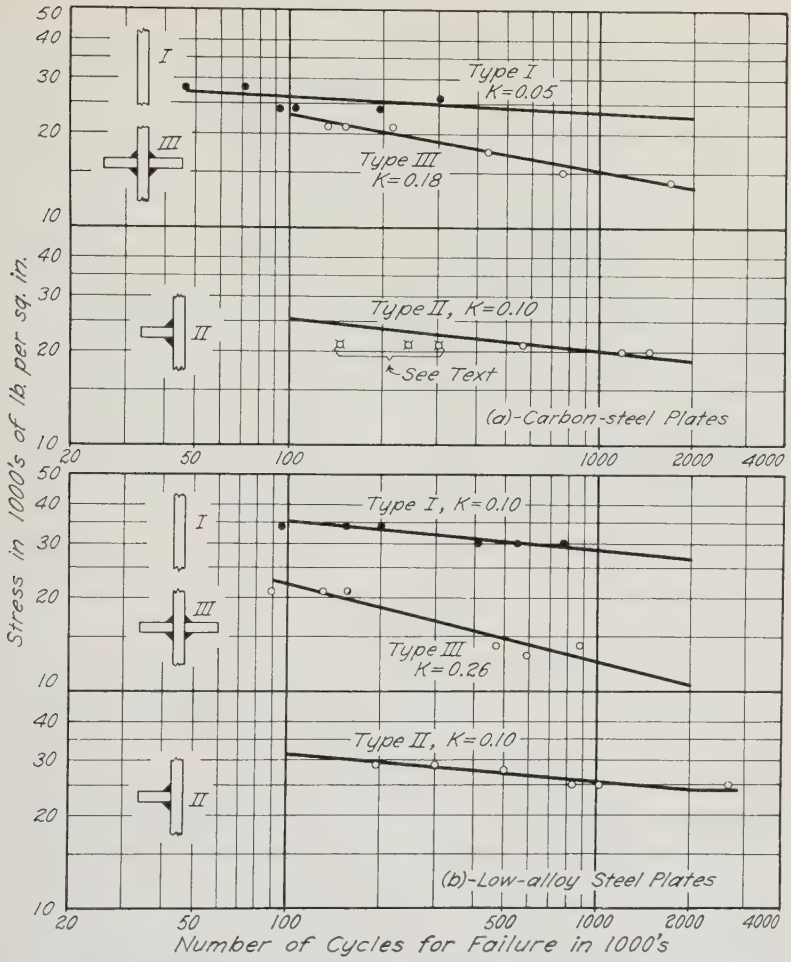


FIG. 32. *S-N* DIAGRAMS FOR CARBON-STEEL PLATES AND LOW-ALLOY-STEEL PLATES

was intended to indicate the probable influence which the bead had upon the fatigue strength of the specimen. The ratings and specimen numbers are listed in Table 34. A description of each rating is given at the foot of the table. The fatigue-strength rating of the same specimens is given in Table 35. The data in Tables 34 and 35 are combined in Table 36. In this table the specimens are separated according to their bead ratings, and also according to the plate materials. The average fatigue-strength rating for each plate material is also given. These averages lose some of their significance due to the fact that, for a

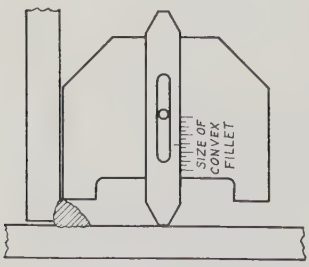
TABLE 33
FATIGUE STRENGTH OF PLATES WITH TRANSVERSE FILLET WELDS
Summary

Kind of Steel	Type of Specimen	Average Fatigue Strength, 1000 lb. per sq. in.	
		$N = 100\,000$	$N = 2\,000\,000$
Carbon	I	25.8	22.8
	II	25.4*	18.9
	III	22.9	13.1
Alloy	I	35.3	26.4
	II	31.7	23.9
	III	22.2	10.1

*Value taken from diagram of Fig. 32 instead of from Table 32 because specimens 7, 8, and 9 broke in the fillet (see text).

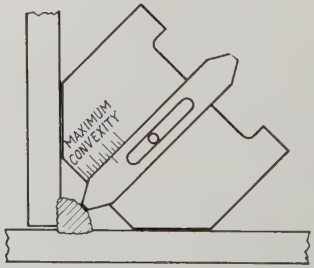
given plate material, most of the specimens of a group had the same bead rating. It is of interest to note, however, that, for a given material, the average fatigue-strength rating had practically the same value for all bead ratings. It would therefore appear that, although the character of the bead had some affect upon the fatigue strength of the specimens, the variations in the beads did not affect the fatigue strength of the specimens tested by more than 5 per cent.

19. *Metallurgical Studies.*—The purpose of the metallurgical studies was to obtain for each type of joint, of each of the two steels,



(a)

To determine size of a convex fillet weld, place gage against toe of shortest leg of fillet and slide pointer out until it touches structure.



(b)

After size of a convex fillet has been determined, place gage against structure and slide pointer out until it touches face of fillet weld.

FIG. 33. BUTT AND FILLET WELD GAGE

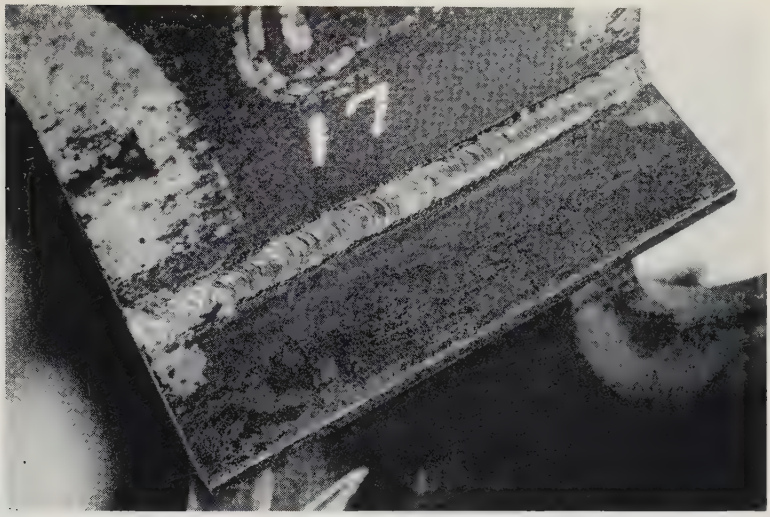


FIG. 34. TYPICAL FILLET WELDS FOR CARBON-STEEL PLATES

the metallurgical character of the joint, and to determine to what extent, if any, the variations of the fatigue values of the welds could be attributed to the metallurgical character of the weld. Metallurgical examinations, consisting of a survey of the microstructure and hard-

FIG. 35. TYPICAL FILLETS OF ALLOY-STEEL PLATES

TABLE 34
RATING OF BEADS FROM PROFILE

Carbon-Steel Specimens				Alloy-Steel Specimens			
Specimen No.	Bead Rating	Specimen No.	Bead Rating	Specimen No.	Bead Rating	Specimen No.	Bead Rating
7	A	13	A	43	A	49	B
8	A	14	B	44	D	50	B
9	A	15	A	45	..	51	A
10	B	16	B	46	B	52	B
11	A	17	C	47	B	53	B
12	A	18	A	48	B	54	B

Rating A: No undercutting, normal convex or concave bead with smooth, concave junction of bead with plate.
Rating B: No undercutting, convex bead with sharp re-entrant angle at junction of weld bead and plate.
Rating C: Undercutting with normal convex or concave bead.
Rating D: Undercutting, convex bead, sharp re-entrant angle.

ness, were made in the weld metal, in the heat-affected zone of the base plate, and in the unaffected plate metal for all specimens. Inasmuch as it developed that all similar specimens had the same metallurgical characteristics, the details are reported for only a few.

The results of the examination of typical specimens of the two steels are shown in Figs. 36 to 40. In these figures the system of designating areas indicated in Fig. 36 was followed, the region of the unaffected base material being represented by *a*, of the heat-affected zone by *b*, and of the weld metal by *c*. Complete hardness surveys were made of each type of welded joint of each of the two steels, but the photomicrographs were taken only of the vital regions and of the areas of unusual interest. Several specimens had fatigue values that were not in agreement with the values of the other specimens. As

TABLE 35
FATIGUE-STRENGTH RATING*

Carbon-Steel Specimens				Alloy-Steel Specimens			
Specimen No.	Fatigue-Strength Rating	Specimen No.	Fatigue-Strength Rating	Specimen No.	Fatigue-Strength Rating	Specimen No.	Fatigue-Strength Rating
7	0.96	13	0.96	43	0.95	49	1.01
8	1.03	14	0.99	44	0.97	50	0.92
9	1.01	15	1.05	45	1.06	51	1.07
10	0.98	16	1.01	46	1.01	52	1.11
11	1.03	17	0.94	47	1.02	53	0.95
12	1.01	18	1.04	48	0.98	54	0.94

*The fatigue-strength rating is the ratio of the fatigue strength of the individual specimen to the average fatigue strength of the group to which the individual belonged.

TABLE 36
RELATION BETWEEN BEAD RATING AND FATIGUE-STRENGTH RATING

Material of Specimens	Bead Rating A		Bead Rating B		Bead Rating C		Bead Rating D	
	Specimen No.	Fatigue-Strength Rating	Specimen No.	Fatigue-Strength Rating	Specimen No.	Fatigue-Strength Rating	Specimen No.	Fatigue-Strength Rating
Carbon Steel	7	0.96	10	0.98	17	0.94		
	8	1.03	14	0.99				
	9	1.01	16	1.01				
	11	1.03						
	12	1.01						
	13	0.96						
	15	1.05						
	18	1.04						
	Av.	1.01		0.99		0.94		
Alloy Steel	43	0.95	46	1.01			44	0.97
	51	1.07	47	1.03				
			48	0.98				
			49	1.01				
			50	0.92				
			52	1.11				
			53	0.95				
			54	0.94				
	Av.	1.01		0.99				0.97

these unusual results could not be attributed to the contour of the weld bead or to other physical discontinuities of the weld joint, the welds were examined for metallurgical discontinuities.

The microstructure and hardness values of the tee and double-tee welded joints of the carbon steel indicated that all areas of the welds had desirable physical properties. The hardness survey of specimen 14, presented in Fig. 36, shows that the maximum hardness in the heat-affected zone of the main plate was less than 180 Vickers, which is below the tentative weldability standard of 200 Vickers set by the American Welding Society. The maximum difference in hardness between the heat-affected zone of the plate and the unaffected plate is 50 Vickers numbers which is well below the maximum safe value.

The structure in the heat-affected zone of the main plate of specimen 8, shown in Fig. 37, was sorbitic, which indicated that this zone had greater strength and ductility than the unaffected plate metal. Region *B*, Fig. 37, shows the root of the weld of specimen 8. Region *C* shows overlapping of the weld metal at the toe of the fillet and also undercutting.

The microstructure and hardness values of the heat-affected zone of alloy-steel specimens showed no indication of any undesirable metallurgical changes due to welding. The variation in hardness for

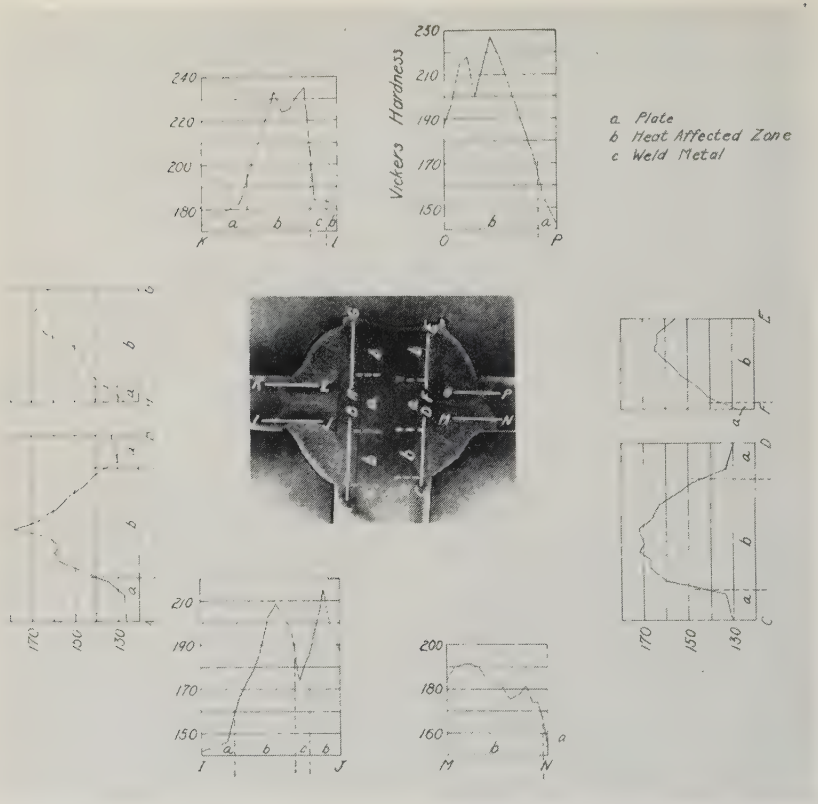


FIG. 36. HARDNESS DIAGRAMS FOR SPECIMEN 14. TYPICAL FOR ALL CARBON-STEEL SPECIMENS

specimen 43, is shown in Fig. 38. The maximum hardness in the heat-affected zone of the alloy-steel specimens did not exceed 230 Vickers, and the maximum hardness variation in the joint did not exceed 50, which is acceptable. The micrographs of the heat-affected zones of the single-tee and double-tee specimens were so similar that the micrographs of specimen 49, shown in Fig. 39, are representative of both types of joints. The structure of the heat-affected zone was sorbitic, as shown by *A*, *B*, *C*, and *D* of the figure.

Figure 38 shows the overlapping of the weld metal at *A*, the toe of the fillet of specimen 43, nevertheless, failure was at *B*. Figure 39 shows overlapping of the weld metal at *G*, the toe of the fillet of specimen 49, the point at which the fatigue crack started; and Fig. 40 shows the path of the fatigue crack through the heat-affected zone.

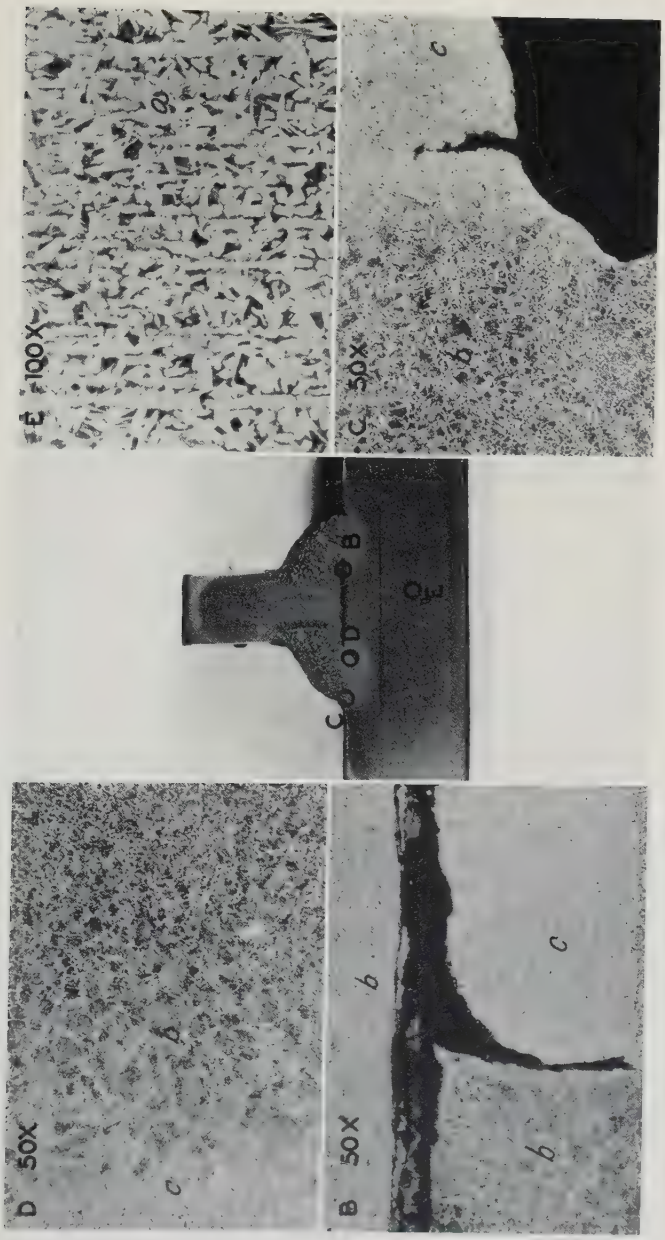
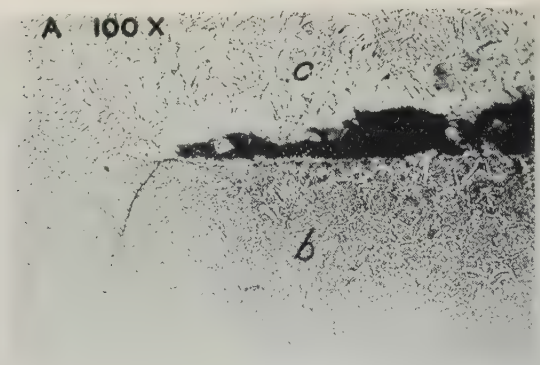
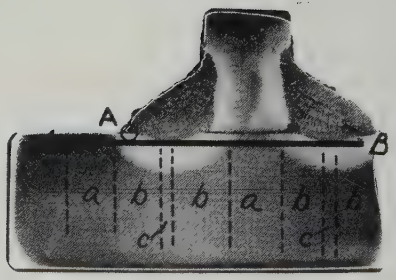


FIG. 37. MICROSTRUCTURE OF SPECIMEN 8. TYPICAL FOR ALL CARBON-STEEL SPECIMENS





a Plate
b Heat Affected Zone
c Weld Metal

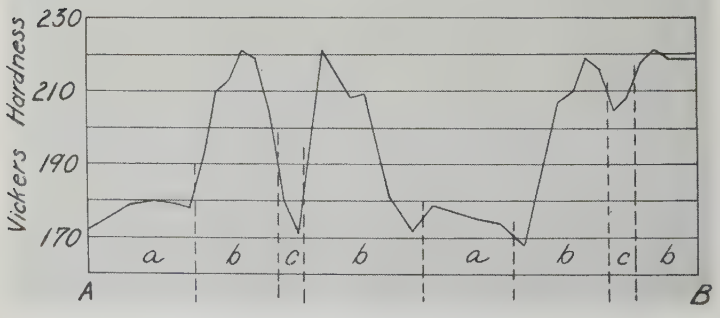


Fig. 38. Hardness Diagrams for Specimen 43. Typical for All Alloy-Steel Specimens

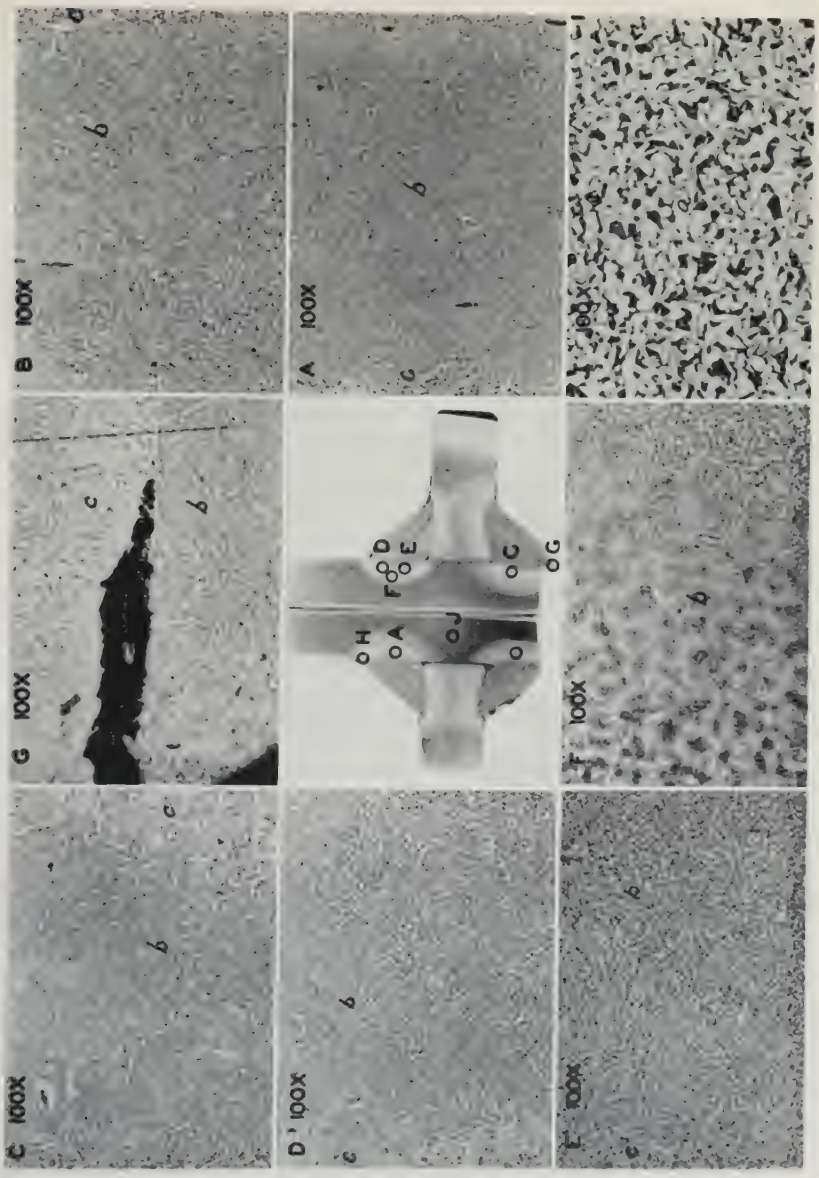


FIG. 39. MICROSTRUCTURE OF SPECIMEN 49. TYPICAL FOR ALL ALLOY STEEL SPECIMENS

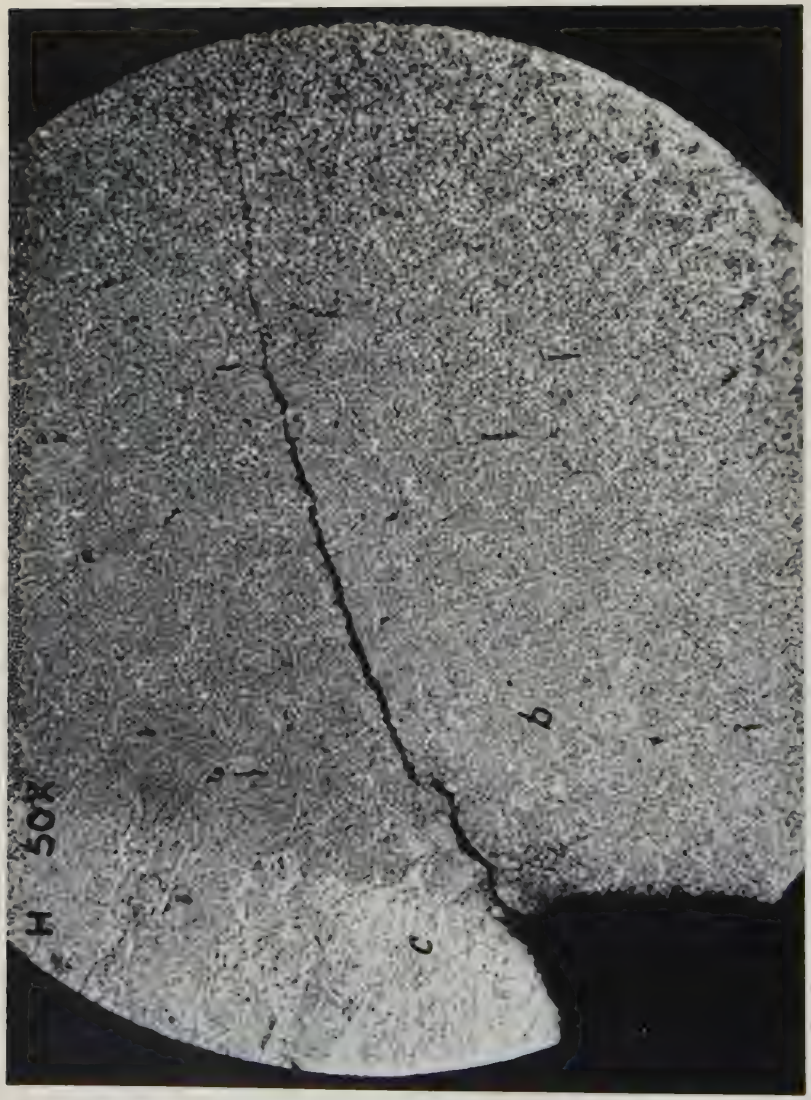


FIG. 40. FATIGUE CRACK THROUGH HEAT-AFFECTED ZONE

The fatigue strength was not, however, significantly lower for these than for other similar specimens.

Figure 39*F* shows the unusual structure of the heat-affected zone of one of the fillet welds. The time and temperature of heating were such that the diffusion of carbon did not produce a homogeneous structure.

The metallurgical changes due to welding were not significant for either the carbon or the alloy steel. The maximum Vickers hardness number was 200 for the carbon steel and 230 for the alloy steel; and the maximum hardness variation in a joint was 50. The welding procedure developed a tough sorbitic structure in the heat-affected zone of both steels.

20. *Summary.*—The values of the fatigue strengths of the individual specimens are given in Tables 31 and 32, and the average values are summarized in Table 33. These results, together with the discussion contained in Sections 18 and 19, apparently justify the following statements:

(1) The fatigue strength of the type I and type II specimens was significantly greater for the alloy steel than it was for the carbon steel. For the type III specimens the fatigue strength for failure at 100 000 cycles was approximately the same for both kinds of steel, but, for failure at a larger number of cycles, the fatigue strength was somewhat less for the alloy than it was for the carbon steel.

(2) The fatigue strength of specimens made of the alloy steel was considerably greater for the type II specimens and somewhat less for the type III specimens than the fatigue strength of butt welds in the alloy-steel plates reported in Table 22, page 49.

(3) The metallurgical changes due to welding were not significant for either the carbon steel or the alloy steel. The maximum hardness, expressed in Vickers numbers, was 200 for the carbon steel and 230 for the alloy steel, and the maximum hardness variation in the joint was 50. The welding procedure developed a tough sorbitic structure in the heat-affected zone of both steels.

(4) The character of the bead had some effect upon the fatigue strength of the specimens, but the variations in the beads for a given base metal probably did not, for the specimens tested, affect the fatigue strength by more than 5 per cent.

VI. Summary of Results

21. *Summary.*—In order to define completely the fatigue strength of a specimen, it is necessary to give the maximum stress in the stress cycle, the ratio of the minimum to the maximum stress, and the number of cycles for failure. The stress cycles used in the tests reported in this bulletin include tension to an equal compression, zero to tension, and tension to tension one-half as great. The corresponding ratios of minimum to maximum stress, designated by r, are -1.0, 0.0, and $+0.5$. Some specimens of each group were tested for failure at a small number of cycles (approximately 100 000) and others for failure at a large number of cycles (approximately 2 000 000). The fatigue strength corresponding to failure at 100 000 cycles and at 2 000 000 cycles was computed from the actual stress and the actual number of cycles for failure by means of the empirical equation $F = S\,(n/N)^K$, in which F is the fatigue strength corresponding to failure at N cycles, S is the maximum stress in the stress cycle which caused failure at n cycles, and K is an experimental constant whose value depends upon the stress-raising characteristics of the specimen. Although it is an empirical equation it is fairly accurate if the ratio n/N does not vary too much from unity.

The tests reported in this bulletin apparently justify the following statements relative to the results obtained from each of the four groups of tests.

Butt Welds in 7/8-in. Carbon-Steel Plates

(1) The average value of the fatigue strength for each group of tests is given in Table 18, page 39, and the effect of the ratio of the minimum to the maximum stress upon the fatigue strength is represented by the diagrams of Fig. 14, page 40.

(2) For specimens in the as-welded condition, the values of the fatigue strength for a cycle in which the stress varied from tension to an equal compression were 22 300 lb. per sq. in. for failure at 100 000 cycles and 14 400 lb. per sq. in. for failure at 2 000 000 cycles, and for a cycle in which the stress varied from zero to tension the values of the fatigue strength were 33 100 lb. per sq. in. for failure at 100 000 cycles and 22 500 lb. per sq. in. for failure at 2 000 000 cycles.

(3) For specimens in the as-welded condition, except that the reinforcement had been machined flush with the base plate on both sides, the values of the fatigue strength for a cycle in which the stress varied from tension to an equal compression were 28 900 lb. per sq. in. for failure at 100 000 cycles and 16 850 lb. per sq. in. for failure at

2 000 000 cycles. These values are considerably higher than corresponding values reported in the preceding paragraph for similar specimens with the reinforcement on.

(4) A comparison of the fatigue strength of butt welds that have been stress-relieved by heat treatment with the fatigue strength of those that have not been stress-relieved indicates that stress-relieving did not affect the fatigue strength. This was true for the specimens with the reinforcement off as well as for those with the reinforcement on.

(5) Specimens from which the reinforcement had been machined flush with the base plate on both sides had approximately the same fatigue strength as plates without welds but with the mill scale on.

(6) Specimens from which the reinforcement had been ground flush with the base plate on both sides with a portable grinder had a fatigue strength only slightly lower than that of similar specimens with the reinforcement machined off.

(7) Specimens with the reinforcement and mill scale machined off and the surfaces polished had a fatigue strength somewhat greater than that of specimens with the mill scale on, but considerably lower than that of small round machined and polished specimens. This latter difference may be due to the size effect.

(8) For all kinds of specimens, stress-relieved or not stress-relieved, reinforcement off or reinforcement on, the fatigue strength corresponding to failure at 2 000 000 repetitions of a cycle in which the stress varied from tension to tension one-half as great exceeded the yield point of the material, and is therefore not important to the structural designer.

Relative Strength of Welded and Riveted Joints in Low-Alloy Steel Plates

(9) The low-alloy structural steel plates had a static strength based on the gross area of 83 000 lb. per sq. in. when fabricated by welding and of 64 800 lb. per sq. in. when fabricated by riveting. The strength of the latter based on the net section was 85 000 lb. per sq. in.

(10) The low-alloy structural steel plates had a fatigue strength based on the gross area and corresponding to failure at 100 000 cycles of 25 000 lb. per sq. in. when fabricated by welding and of 19 800 lb. per sq. in. when fabricated by riveting. For failure at 2 000 000 cycles, the corresponding values were 15 000 lb. per sq. in. and 13 800 lb. per sq. in. for welded and riveted joints, respectively. These values

of the fatigue strength are for a cycle in which the stress varied from tension to an equal compression.

(11) The fatigue cracks in the riveted specimens passed through the holes in the outer row. Those in the welded specimens always began at the edge of the deposited metal where the abrupt change in section acted as a stress raiser that extended the full width of the specimen.

Effect of Periods of Rest Upon Fatigue Strength of Butt Welds

(12) The specimens, which were as nearly identical as it was feasible to make them, were divided into three groups. One group was subjected to continuous tests, a second group was subjected to an intermittent test in which a specimen was subjected to a 5-min. rest period after each 100 cycles, and a third group was subjected to an intermittent test in which a specimen was subjected to a 30-min. rest period after each 100 cycles. The average results of the fatigue tests are given in Table 27, page 62.

(13) The difference between the fatigue strengths given by rest tests and by continuous tests had an average value of 5 per cent and a maximum value for any one series of 10 per cent, the values obtained from the rest tests being slightly less than those obtained from the continuous tests. It would appear, therefore, that rest periods did not have a significant effect upon the fatigue strength of the welded joints.

Effect of Transverse Fillet Welds Upon the Fatigue Strength of Steel Plates

(14) The details of the specimens are given in Fig. 30, page 63, and the average results of the fatigue tests are given in Table 33, page 70.

(15) The fatigue strength of the type I and type II specimens (see Fig. 30) was significantly greater for the alloy steel than it was for the carbon steel. For the type III specimens the fatigue strength for failure at 100 000 cycles was approximately the same for both kinds of steel, but, for failure at a larger number of cycles, the fatigue strength was somewhat less for the alloy than it was for the carbon steel.

(16) The fatigue strength of specimens made of the alloy steel was considerably greater for the type II specimens and somewhat less for the type III specimens than the fatigue strength of butt welds in the alloy-steel plates reported in Table 22, page 49.

(17) The metallurgical changes due to welding were not significant

for either the carbon steel or the alloy steel. The maximum hardness, expressed in Vickers numbers, was 200 for the carbon steel and 230 for the alloy steel, and the maximum hardness variation in the joint was 50. The welding procedure developed a tough sorbitic structure in the heat-affected zone of both steels.

(18) The character of the bead had some effect upon the fatigue strength of the specimens, but the variations in the beads for a given base metal probably did not, for the specimens tested, affect the fatigue strength by more than 5 per cent.

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